**From:** Jefferson Cole
**To:** Ohrel, Sara
**CC:** Cole, Jefferson
**Sent:** 2/22/2014 7:13:47 PM
**Subject:** Slides for OAQPS v1 --Deliberative--
**Attachments:** Biomass Update with OAQPS - 2014.02.21 - v1.pptx

Sara,

I hope your weekend is going well. I've attached a first draft of slides for our discussion with OAQPS technical folks on Monday.

A few things regarding my thoughts on how we should approach the briefing, and how that influenced how I made up the slides.

1. I believe we should keep things short and sweet at the beginning, getting right to the point of the main ideas we want to make sure they remember.

2. We should probably spend more than a few minutes walking through the main document, rather than just giving them a skim of the document.

3. I've left in some slides from our last briefing with Anna, since it may prove useful if folks need a refresher on background stuff. I do not think that we should spend time upfront on that Ex. 5 - Deliberative Ex. 5 - Deliberative Of course, there may be some technical folks there that may be new to this. In that case, let's stick with a simple 2 min explanation at the beginning.

4. I have a small comment for you on Ex. 5 - Deliberative Ex. 5 - Deliberative Ex. 5 - Deliberative

5. Ex. 5 - Deliberative

Let me know if you have any questions. I will likely be around tomorrow if you want to chat about any of this.

Thanks, and best of luck with the rest of the main doc.

Jeff

| | |
|---|---|
| **From:** | Ohrel, Sara |
| **To:** | Kocchi, Suzanne |
| **Sent:** | 2/21/2014 4:21:12 PM |
| **Subject:** | Fw: Definition of “forest products manufacturing residuals” |
| **Attachments:** | image002.jpg; Letter to J Santiago re Def Manufacturing Residuals 022114 FINAL.pdf |

Also sent to the rest of team biomass

---

**From:** Missimer, Katie <Katie_Missimer@afandpa.org> on behalf of Noe, Paul <Paul_Noe@afandpa.org>
**Sent:** Friday, February 21, 2014 2:49:23 PM
**To:** Santiago, Juan
**Cc:** Goffman, Joseph; Dunham, Sarah; Wood, Anna; Gunning, Paul; Ohrel, Sara; Tim_hunt@afandpa.org; Tsang, Linda; Lancey, Stan
**Subject:** Definition of “forest products manufacturing residuals”

AMERICAN WOOD COUNCIL

American Forest & Paper Association

Dear Juan:

As a follow up to our discussion last December on the timing and development of EPA's Biogenic $CO_2$ Accounting Framework and the definition of manufacturing residuals, we would like to provide for your consideration the attached definition of the “forest products manufacturing residuals” that could be incorporated into the Framework and permitting regulations.

Please contact me if you have any questions.

Thank you.

**Paul Noe**
Vice President for Public Policy
Paul_Noe@afandpa.org
(202) 463-2777
AMERICAN FOREST & PAPER ASSOCIATION
1101 K Street, N.W., Suite 700
Washington, D.C. 20005

**American Forest & Paper Association**

February 21, 2014

Mr. Juan Santiago
U.S. Environmental Protection Agency
109 T.W. Alexander Drive
Mail Code: C504-01
Research Triangle Park, NC 27709

**Re: Definition of Forest Product Manufacturing Residuals**

Dear Mr. Santiago:

In December, 2013, AF&PA staff discussed with you the timing and development of EPA's Biogenic $CO_2$ Accounting Framework and the definition of manufacturing residuals. Following up on that discussion as well as the NCASI report we provided to you and your staff, "Greenhouse Gas and Fossil Fuel Reduction Benefits of Using Biomass Manufacturing Residuals for Energy Production in Forest Products Facilities", we would like to provide for your consideration a definition of the "forest products manufacturing residuals" that could be incorporated into the Framework and permitting regulations.

As you know, the forest products industry uses biomass residuals from the manufacturing process for its primary energy source. Unlike power plants and other biomass energy facilities, the creation and use of biomass energy in forest products mills is integral and incidental to the manufacture of products such as pulp, paper, packaging and wood products. Pulp mills, integrated paper mills and wood products mills convert biomass residuals to energy for manufacturing bio-based products. To the extent feasible, the wood biomass entering the mills is used to create these higher value products. The use of the residuals for energy is a highly sustainable use of those materials. Indeed, it would be unsustainable not to use the residuals for energy. In addition, recognizing that combustion of forest products manufacturing residuals for energy as carbon neutral helps to promote the use of renewable energy.

AF&PA proposes that EPA use the following definition for "forest products manufacturing residuals" in the Biogenic $CO_2$ Accounting Framework and corresponding regulations:

*"Forest products manufacturing residuals" are defined as forest-derived biomass from pulp and paper mills, wood products manufacturing facilities, and downstream manufacturing facilities including, but not limited to:*

- *spent pulping liquors (e.g., black liquor, red liquor, liquor solids) and pulping by-products and substances (e.g., rectified methanol, black liquor soap, red oil, lignin);*
- *woody manufacturing residuals, such as:*

- *wood product process residuals (e.g., bark, sawdust, shavings, sander dust, resinated wood residuals, veneer residuals, slabs, cutoffs, knots, woody residuals from air emission control systems, manufactured wood residuals (e.g., furniture, crate and pallet plant residuals);*
- *pulping, paper, and converting process residuals (e.g., bark, knots, shives, non-recoverable trim and broke);*
- *off-specification materials; reinjection char (unburnt biomass); paper machine cleaner, screening and other rejects; and*
- *similar residuals;*

* *paper recycling residuals (e.g., materials removed from recovered paper and paperboard during the recycling process, such as non-recyclable fiber or old corrugated containers rejects); and*
* *wastewater and process water treatment plant residuals.*

We believe that this definition captures the various categories of manufacturing residuals that are most commonly used by the forest products industry for energy. To be clear, we believe other types of biomass materials should also be considered carbon neutral but the focus of this letter is to provide you the above definition for manufacturing residuals from forest products.

If you would like to further discuss this issue, please contact me at Paul_Noe@afandpa.org or 202-463-2777 or Linda Tsang at Linda_Tsang@afandpa.org or 202-463-2752.

Respectfully submitted,

Paul Noe
Vice President, Public Policy

cc: Joseph Goffman
Sarah Dunham
Anna Wood
Paul Gunning
Sara Ohrel

| | |
|---|---|
| **From:** | Ohrel, Sara |
| **To:** | Hanks, Katie P. |
| **Sent:** | 2/7/2014 12:49:38 PM |
| **Subject:** | RE: Task summary |

Thank you, Katie. This work you are conducting will be invaluable to us. I really appreciate the efforts from you and your team J

---

**From:** Hanks, Katie P. [mailto:kphanks@rti.org]
**Sent:** Friday, February 07, 2014 12:44 PM
**To:** Ohrel, Sara
**Subject:** RE: Task summary

Sounds like a plan. Thanks.

Katie Hanks
RTI International
3040 Cornwallis Road
Research Triangle Park, NC 27709
(919) 316-3732
(919) 541-7155 (fax)

---

**From:** Ohrel, Sara [mailto:Ohrel.Sara@epa.gov]
**Sent:** Friday, February 07, 2014 12:33 PM
**To:** Hanks, Katie P.
**Cc:** Boone, Stephen; Baker, Justin; Beach, Robert H.; Cole, Jefferson
**Subject:** RE: Task summary

Thank you Katie. This mirrors our conversation earlier this week and I agree with all the tasks you have outlined. However, I have one friendly amendment to number 1: **Ex. 5 - Deliberative**

**Ex. 5 - Deliberative**

On number 3, please send your analysis of part 51 as you finish it (rather than waiting for the other components – 52, 70 and 71 - to also be complete).

Thank you so much!
Sara

---

**From:** Hanks, Katie P. [mailto:kphanks@rti.org]
**Sent:** Thursday, February 06, 2014 4:55 PM
**To:** Ohrel, Sara
**Cc:** Boone, Stephen; Baker, Justin; Beach, Robert H.
**Subject:** Task summary

Below is a brief summary of the tasks we discussed on our call yesterday.

# Ex. 5 - Deliberative

# Ex. 5 - Deliberative

Katie Hanks
RTI International
3040 Cornwallis Road
Research Triangle Park, NC 27709
(919) 316-3732
(919) 541-7155 (fax)

| | |
|---|---|
| **From:** | Ohrel, Sara |
| **To:** | Cole, Jefferson |
| **Sent:** | 2/6/2014 9:50:02 AM |
| **Subject:** | 2 more |
| **Attachments:** | FABA Case Study Calcs 1-20-2014_(ratios) SO.xlsx; TO003_REVISED_Appendix GSpreadsheet_1-21-2014 JC (ratios)so.xlsx |

Sara Bushey Ohrel
Climate Economics Branch
Climate Change Division
U.S. Environmental Protection Agency
Phone: (202) 343-9712
Cell: (202) 341-6748

--this email is deliberative--do not distribute or cite--

**From:** Ohrel, Sara
**To:** Latta, Greg; Beach, Robert H.; Baker, Justin
**Sent:** 2/5/2014 1:15:10 PM
**Subject:** for today's discussion
**Attachments:** equation and questions 2 3 14v2_gl so.docx

Sara Bushey Ohrel
Climate Economics Branch
Climate Change Division
U.S. Environmental Protection Agency
Phone: (202) 343-9712
Cell: (202) 341-6748

--this email is deliberative--do not distribute or cite--

**From:** Latta, Greg
**To:** Ohrel, Sara
**Sent:** 2/3/2014 9:10:43 PM
**Subject:** RE: Re:
**Attachments:** equation and questions 2 3 14v2_gl.docx

Sorry. Some thoughts in doc.

**From:** Ohrel, Sara [mailto:Ohrel.Sara@epa.gov]
**Sent:** Monday, February 03, 2014 5:47 PM
**To:** Latta, Greg
**Subject:** Re:

Hi Greg,
Unless I hear from you soon, I will continue on with the version I sent you in the am. Thanks again!

**From:** Ohrel, Sara
**Sent:** Monday, February 03, 2014 6:18:12 PM
**To:** Latta, Greg
**Subject:** RE:

Sorry this is late – I needed to shovel before it got to dark. Here is what I have. Please send back your edits/initial thoughts/whatever you have time for before you go and I will pick up in the am.
Thank you!!!!!

Sara Bushey Ohrel
Climate Economics Branch
Climate Change Division
U.S. Environmental Protection Agency
Phone: (202) 343-9712
Cell: (202) 341-6748



**From:** Latta, Greg [mailto:greg.latta@oregonstate.edu]
**Sent:** Monday, February 03, 2014 2:16 PM
**To:** Ohrel, Sara
**Subject:** RE:

Ex. 5 - Deliberative

# Ex. 5 - Deliberative

**From:** Ohrel, Sara [mailto:Ohrel.Sara@epa.gov]
**Sent:** Monday, February 03, 2014 11:03 AM
**To:** Latta, Greg
**Subject:**

**Ex. 5 - Deliberative**

Sara Bushey Ohrel
Climate Economics Branch
Climate Change Division
U.S. Environmental Protection Agency
Phone: (202) 343-9712
Cell: (202) 341-6748

--this email is deliberative--do not distribute or cite--

---

**From:** Ohrel, Sara
**To:** Kornylak, Vera S.; Montanez, Jessica
**Sent:** 2/3/2014 6:05:26 PM
**Subject:** slides we plan to use for tomorrow's briefing
**Attachments:** Biomass update with Anna and Paul 2 4 14_draft 2 3 14.pptx

Hello Jessica and Vera,

Attached are the slides that we plan to use for our briefing with Paul and Anna tomorrow. Please let me know if you have any questions or additions. If you could please send any additions by noon so I can then send it around to the entire group, that would be great.

Thank you,
Sara

Sara Bushey Ohrel
Climate Economics Branch
Climate Change Division
U.S. Environmental Protection Agency
Phone: (202) 343-9712
Cell: (202) 341-6748

--this email is deliberative--do not distribute or cite--

**From:** Latta, Greg
**To:** Ohrel, Sara
**Sent:** 2/2/2014 3:10:06 PM
**Subject:** RE: for discussion: deliberative

OK I think we are probably going to need to talk this through. Ex. 5 - Deliberative

Ex. 5 - Deliberative

Would it be possible to do our Monday talk either at 8:00pst (11est) or 10pst(1est) rather than 8:30?

-----Original Message-----
From: Ohrel, Sara [mailto:Ohrel.Sara@epa.gov]
Sent: Sunday, February 02, 2014 8:47 AM
To: Latta, Greg
Subject: RE: for discussion: deliberative

Thanks Greg. I think that we are on the same page in many respects.
Please take a look at the attached doc where Ex. 5 - Deliberative
Ex. 5 - Deliberative
send any comments (or we can chat if easier).
Thanks!

Sara Bushey Ohrel
Climate Economics Branch
Climate Change Division
U.S. Environmental Protection Agency
Phone: (202) 343-9712
Cell: (202) 341-6748

--this email is deliberative--do not distribute or cite--

-----Original Message-----
From: Latta, Greg [mailto:greg.latta@oregonstate.edu]
Sent: Sunday, February 02, 2014 10:22 AM
To: Ohrel, Sara
Subject: RE: for discussion

Ex. 5 - Deliberative

Ex. 5 - Deliberative

At this point what I think is best is:

Ex. 5 - Deliberative

_______________________________________

From: Ohrel, Sara [Ohrel.Sara@epa.gov]
Sent: Sunday, February 02, 2014 5:47 AM
To: Latta, Greg
Subject: Re: for discussion

That's great, both beer mode and successful steer weighing!
I agree Ex. 5 - Deliberative
Ex. 5 - Deliberative

_______________________________

From: Latta, Greg <greg.latta@oregonstate.edu>
Sent: Saturday, February 01, 2014 6:06:40 PM
To: Ohrel, Sara
Subject: Re: for discussion

Done skiing in beer mode. Gwen did a great job covering for Emma at the steer weigh-in (he was 892lbs which is almost 1000 lbs more than Sven at this same time).

Ex. 5 - Deliberative

Sara Bushey Ohrel
Climate Economics Branch
Climate Change Division
U.S. Environmental Protection Agency
Phone: (202) 343-9712
Cell: (202) 341-6748

--this email is deliberative--do not distribute or cite--

From: Latta, Greg [mailto:greg.latta@oregonstate.edu]
Sent: Friday, January 31, 2014 11:19 PM
To: Ohrel, Sara
Subject: RE: for discussion

OK. So the long and short of it is that I think (as Jeff had suggested) it should be

**Ex. 5 - Deliberative**

**Ex. 5 - Deliberative**

From: Ohrel, Sara [mailto:Ohrel.Sara@epa.gov]
Sent: Friday, January 31, 2014 4:07 PM
To: Latta, Greg
Subject: Re: for discussion

Thanks for trying (our stuff is so much cooler and actually would've had input..!).
Ok, thanks. What is this steer's name?

________________________________
From: Latta, Greg <greg.latta@oregonstate.edu<mailto:greg.latta@oregonstate.edu>>
Sent: Friday, January 31, 2014 6:45:32 PM
To: Ohrel, Sara
Subject: Re: for discussion

Met with the grad students who want to do an internship and pitched the GHG projections review and they want to stick with RINs.

I am off to help Emma with the steer and then I will look over the doc.

"Ohrel, Sara" <Ohrel.Sara@epa.gov<mailto:Ohrel.Sara@epa.gov>> wrote:
deliberative

Sara Bushey Ohrel
Climate Economics Branch
Climate Change Division
U.S. Environmental Protection Agency
Phone: (202) 343-9712
Cell: (202) 341-6748

--this email is deliberative--do not distribute or cite--

**From:** Latta, Greg
**To:** Cole, Jefferson; Ohrel, Sara; 'Justin Baker'
**CC:** Ex. 6 - Personal Privacy
**Sent:** 1/31/2014 11:13:57 PM
**Subject:** RE: new doc --DELIBERATIVE--
**Attachments:** GregTest.xlsx

Jeff, Sara, Justin,

I agree. Ex. 5 - Deliberative

Ex. 5 - Deliberative

Greg

Attached is a worksheet I was playing with. Taking a cue from Jeff's Ex. 5 - Deliberative

Ex. 5 - Deliberative

---

**From:** Cole, Jefferson [mailto:Cole.Jefferson@epa.gov]
**Sent:** Friday, January 31, 2014 9:24 AM
**To:** Latta, Greg; Ohrel, Sara; Justin Baker
**Cc:** Ex. 6 - Personal Privacy
**Subject:** RE: new doc --DELIBERATIVE--

Hi Greg,

I've been thinking more about the reformulation here, and the only outstanding question I have right now, is that

Ex. 5 - Deliberative

What do you think?

Lastly, I will be out of town for the next several days, so you may not hear back from me directly. I did copy my personal email in case I am able to respond from afar.

Thanks,

Jeff

---

**From:** Cole, Jefferson
**Sent:** Wednesday, January 29, 2014 12:14 PM
**To:** Greg Latta; Ohrel, Sara; Justin Baker
**Subject:** Re: new doc

Many thanks.

---

**From:** Latta, Greg <greg.latta@oregonstate.edu>
**Sent:** Wednesday, January 29, 2014 12:13:32 PM
**To:** Ohrel, Sara; 'Justin Baker'; Cole, Jefferson
**Subject:** new doc

enjoy

| | |
|---|---|
| **From:** | Ohrel, Sara |
| **To:** | Latta, Greg |
| **Sent:** | 1/31/2014 2:11:14 PM |
| **Subject:** | pathways docs |
| **Attachments:** | Black Liquor and boundaries.docx; Black Liquor Pathways 10 25 12.pptx; TO 003_Memorandum_Treatment of Secondary Feedstocks in the Biogenic Accounting Framework_10-10-2012_SO.docx |

Sara Bushey Ohrel
Climate Economics Branch
Climate Change Division
U.S. Environmental Protection Agency
Phone: (202) 343-9712
Cell: (202) 341-6748

--this email is deliberative--do not distribute or cite--

| | |
|---|---|
| **From:** | Skog, Kenneth E -FS |
| **To:** | Hohenstein, William - OCE; Ohrel, Sara; Buford, Marilyn -FS; Reid Miner (RMiner@NCASI.org) |
| **CC:** | Matthew Russell (russellm@umn.edu); Woodall, Christopher W -FS |
| **Sent:** | 1/31/2014 9:26:38 AM |
| **Subject:** | Decay rates for forest residue in the Eastern US based on FIA plot data |
| **Attachments:** | ECO-13-0271.R1.pdf |

All,

Attached is a benchmark paper that has been accepted for publication in Ecosystems on the decay of downed woody material in forests in the Eastern United States. It is based on FIA plot remeasurement data. The paper gives k (decay rate) values and associated half lives by species and climate zone. A key caveat is that it indicates decay to the point where there is no detectable wood form. There is some residual amount, not estimated, that becomes part of soil carbon. So in that sense these are partial decay estimates.

I am sending this because I think it is key information that helps inform – in some detail - the alternate decay fate of logging residue that will decay in the forest if not removed for an alternate use such as energy production.

Please let us know (Matt Russell was the lead author) if you have questions.

Ken Skog

Ken Skog
Project Leader, Economics, Statistics and Life Cycle Analysis Research
USDA Forest Service, Forest Products Laboratory
One Gifford Pinchot Drive, Madison, WI 53726-2398
Phone: 608-231-9360 Fax; 608-231-9508
Cell: 608-658-2614 kskog@fs.fed.us

---

**From:** Matthew Russell [mailto:russellm@umn.edu]
**Sent:** Friday, January 31, 2014 8:09 AM
**To:** Skog, Kenneth E -FS
**Subject:** Re: Ecosystems - Manuscript ECO-13-0272.R1

Hi Ken,

I attached the final version of the MS that has been accepted (but isn't formatted for the publication of course.) I'll forward whatever the journal gives me for proofs when available.

Thanks,

Matt

On 1/31/2014 7:45 AM, Skog, Kenneth E -FS wrote:
Matt,
When you have an in press version (or other appropriate version) I would be interested in sending this to some folks at EPA and the USDA Climate change program office.
Thank you,
Ken

Ken Skog
Project Leader, Economics, Statistics and Life Cycle Analysis Research
USDA Forest Service, Forest Products Laboratory
One Gifford Pinchot Drive, Madison, WI 53726-2398
Phone: 608-231-9360 Fax; 608-231-9508
Cell: 608-658-2614 kskog@fs.fed.us

---

**From:** Matthew Russell [mailto:russellm@umn.edu]
**Sent:** Thursday, January 30, 2014 3:51 PM
**To:** Woodall, Christopher W -FS; damato@umn.edu; Shawn Fraver; Domke, Grant M -FS; Skog, Kenneth E -FS
**Subject:** Fwd: Ecosystems - Manuscript ECO-13-0272.R1

Hi all,

Here is some good news from Ecosystems regarding our downed woody debris paper. Finally happy to have this in press after a year in review! I've forward the few image files that the Editorial Office needs.

Thanks again for your help in shaping this work. I'll keep everyone posted when I see this posted online.

Matt

-------- Original Message --------
**Subject:** Ecosystems - Manuscript ECO-13-0272.R1
**Date:** Thu, 30 Jan 2014 15:10:09 -0500 (EST)
**From:** ecosys@zoology.wisc.edu
**To:** russellm@umn.edu
**CC:** hhs@virginia.edu

```
Date: 30-Jan-2014

Dr. Matthew Russell
1530 Cleveland Ave. N
St. Paul, Minnesota 55108

RE: Residence time and decay rates of downed woody debris biomass/carbon in eastern US forests

Dear Dr. Russell:

Dr. Herman Shugart, the subject-matter editor, recommends accepting your paper.  I have reviewe

Please be sure to forward the following items to Suzann McClenahan in the Editorial Office (eco

(1) Individual, high-resolution TIF files for the figures in Appendix C and D
```

You will be contacted by a representative of our publisher concerning copyright transfer agreem

The editors invite you to submit slide images associated with your accepted paper (or concernin

Thank you for submitting your work to ECOSYSTEMS.

Sincerely,

Dr. Monica Turner
Co-Editor-in-Chief

SUBJECT-MATTER EDITOR'S COMMENTS FOR AUTHORS
Subject-Matter Editor: Shugart, Herman
Comments to the Author:
Your responses to the reviewer's comments seem appropriate. Thank you for your effort.

SELECTION CRITERIA/INFORMATION FOR ECOSYSTEMS COVER IMAGES

* Attractive, striking image; vibrant colors; good contrast; in focus

* Image works well, or can be cropped to work well, with other Ecosystems cover elements: title, abbreviated contents, bar code and logos, etc.

* Images should vary noticeably from issue to issue (i.e. aerial vs. ground level, terrestrial vs. aquatic, etc.)

* Image should ideally be of an entire ecosystem

* Cover image should be related to an article in the issue

* We must obtain legal rights to the image. If it is drawn directly from an article (i.e. we are also publishing it IN the journal) then we have the rights. If it is not part of an article then whoever provides the image must assign us the rights to use it on the cover of the print edition, in the electronic edition, and in any promotional uses.

# Residence time and decay rates of downed woody debris biomass/carbon in eastern US forests

| | |
|---|---|
| Journal: | *Ecosystems* |
| Manuscript ID: | ECO-13-0272.R1 |
| Types: | Original Article |
| Date Submitted by the Author: | n/a |
| Complete List of Authors: | Russell, Matthew; University of Minnesota, Department of Forest Resources<br>Woodall, Christopher; USDA Forest Service, Northern Research Station<br>Fraver, Shawn; University of Maine, School of Forest Resources<br>D'Amato, Anthony; University of Minnesota, Department of Forest Resources<br>Domke, Grant; USDA Forest Service, Northern Research Station<br>Skog, Kenneth; USDA Forest Service, Forest Products Laboratory |
| Key Words: | carbon flux, decomposition, forest inventory, forest fuels, decay class, coarse woody debris |
| | |

UNIVERSITY OF MINNESOTA

*Twin Cities Campus*

***Department of Forest Resources***
*College of Food, Agricultural and Natural Resource Sciences*

*115 Green Hall*
*1530 Cleveland Avenue N*
*St. Paul, MN 55108-6112*
*Office: 612-626-4280*
*Fax: 612-625-5212*
*www.forestry.umn.edu*

12 January 2014

*Ecosystems*
1002 Stonebriar Drive
Verona, WI 53593, USA

Dr. Monica G. Turner:

The manuscript titled **"Residence time and decay rates of downed woody debris biomass/carbon in eastern US forests"**, authored by Matthew B. Russell, Christopher W. Woodall, Shawn Fraver, Anthony W. D'Amato, Grant M. Domke, and Kenneth E. Skog has undergone minor revisions and is being resubmitted for publication in *Ecosystems*.

We thank Dr. Herman Shugart, Dr. Lori Daniels, and the anonymous reviewer for providing useful feedback on this work. We sincerely believe that we have addressed each of the comments in this revised version. These changes are particularly emphasized by (1) restructuring the description of the analytical procedures and data used in the modeling efforts, (2) listing of key assumptions carried out in the analysis, and (3) clarifying how log length was specified in the modeling analysis.

In the pages that follow, you will see the reviewers' comments followed by our comments in italics. Line and page numbers reference the current version of the manuscript.

We look forward to hearing your analysis of these revisions and appreciate the opportunity to share these results with the *Ecosystems* audience. Thank you for your consideration.

Sincerely,

Matthew Russell
Research Associate
russellm@umn.edu

cc. Christopher W. Woodall
Shawn Fraver
Anthony W. D'Amato
Grant M. Domke
Kenneth E. Skog

**In response to comments from the Subject-Matter Editor:**

The reviewers have provided what should prove to be useful comments for a revision of your manuscript. Please respond to the comments accordingly and provide a list of how you responded. Please recall that the reviewer's comments spring from the impressions of colleagues in your field and should be remedied even if you maintain your conclusions. The one set of comments regarding the lack of appreciation of modern quantitative ecological methods by the Ecosystems readership, if it is correct, should be corrected. Please develop the modeling sections of the paper with clarity and confidence.

*We thank the Subject-Matter Editor for coordinating the review process and for summarizing key concerns raised by the reviewers. A significant revision in this draft restructures some of the analytical procedures and quantitative methods implemented in the study. We feel that this revision succinctly presents the modeling aspects of the paper with the appropriate amount of detail for the Ecosystems audience. Specific comments on these changes appear below in the response to the individual reviewers.*

**In response to comments from Reviewer 1:**

Review of Russell et al.
Residence time and rate of decay for downed woody debris biomass/carbon in eastern US forests

Journal: Ecosystems
Manuscript ID: ECO-13-0272

Because of the growing significance of understanding the dynamics of carbon storage in the downed woody debris component of eastern forests, an assessment of the decomposition rates of a wide variety of tree species is very welcome and valuable. As the authors state, previous studies have relied too heavily on the use of density changes as a surrogate for mass (and carbon) loss estimates. Consequently, this manuscript attempts to advance our understanding considerably by co-considering density changes and mass loss over time.

If the modeling analysis can be relied on, the reported results of half-lives, residence times, and decay constants give us quite valuable information. These results did not contain many surprises, as expected, but it would be extremely useful to have the specific values for each of these parameters reported by this manuscript for modeling and other purposes, and for so many key species. Of particular importance are the estimates of the relationships between temperature and decay rates for the range of species, although these estimates receive only minor attention in the manuscript.

The central question of this manuscript is whether a model of woody debris decomposition can be trusted to reliably fill in the gaps that remain from the existed field studies. This study relies heavily on the analysis of Russell et al. 2013 that estimated the probabilities of woody debris transitioning from one decay class to another over time. I was hoping to find a strong clear linkage between the carbon content of material in a given decomposition class, the nature of the decay processes prevalent in that class, and the transition probabilities of material moving between classes. However, I found this linkage still quite dependent on a range of assumptions.

*We thank the reviewer for their concerns. We agree that most studies disregard volume losses and rely on changes in density alone to infer deadwood carbon dynamics. We maintain that decay class transitions can be used as a surrogate for reductions in DWD density and mass through time. Emerging work by Harmon et al. (2013; For. Ecol. and Manage. 291 259-267) indicates that carbon content may be slightly greater for DWD in latter decay classes. Although somewhat out of the scope of this analysis, we have included the Harmon et al. reference in the Discussion (line 333).*

*See the Discussion section on lines 350-355 (and more comments below) where we have restated some of our main assumptions used throughout the analysis.*

Representing the process of moving between decay classes as equivalent to a classical decay with a "k" coefficient is a leap I am uncomfortable with. I understand that using these "k" values in broad spectrum ecosystem carbon flux models is likely to give a reasonable ability to predict carbon stock changes. However, it is important to understand that class transitions are being modeled, simplifying a variety of co-occurring processes, and far from the more simple set of processes that are depicted as "k" decay rates for leaf litter.

One of the problems is that the decay class is descriptive of a variety of wood conditions (e.g. Class 4 is "Heartwood rotten; piece does not support its own weight, but maintains its shape" with a texture of "Soft, small blocky pieces; a metal pin can be pushed into heartwood"). There is no single chemical state that defines a class, or that identifies the transitions that occur when material moves into a clearly different chemical state in the next class.

*We agree that decay class is a subjective determination of the state of a log's decomposition, however, decay class systems are used in field inventories worldwide. Given that our objective is in quantifying the decomposition of DWD that meets the inventory's specification (e.g., small-end diameter > 7.6 cm), we are confident that decay classes may be used to infer the k decomposition parameters. It was our hope that by only presenting species-specific estimates for which there are plentiful observations (n>20), measurement error associated with the subjective determination of decay class would be minimized. Were we to analyze other ecosystem C pools, i.e., leaf litter or fine woody debris, we agree that a different method would be required given the faster rate of decomposition associated with those pools.*

There is enormous difficulty in taking a process such as woody decay that occurs only very slowly and knowing exactly how much carbon is released over each time period of the existence of that dead wood. It would be wonderful if we could track individual pieces of wood in many different environments. The forest debris class datasets such as those analyzed by Russell et al. 2013 and this manuscript probably give us as strong a picture of forest woody debris processing that we currently can hope for. However, it is still a long way from this data to our ability to confidently state we can capture the dynamics by a simple set of decay equations. These equations are fine for large scale modeling predictions, but as yet contain too much uncertainty to give us confidence that we can predict wood debris dynamics in a specific forest and under a specific set of conditions.

*We agree that tracking individual pieces of woody debris is a tremendous investment in field efforts. By using the results observed here, we understand that there may be a large cloud of uncertainty when attempting to predict carbon loss on individual logs found in specific environments. Instead, we hope the scope of the manuscript is centered on precisely the large-scale modeling efforts to which the reviewer refers. With regard to uncertainty, we hope that we have provided sufficient measures of uncertainty for the analysis that we considered (e.g., by providing standard errors for k parameters in Tables 2-3 and standard deviations in Figure 1), but recognize that our assumptions (lines 350-355) may require testing to arrive at the true uncertainty.*

It is difficult to know whether some of the assumptions made by the authors (for example, applying generic volume reduction factors observed in a few species to all species, page 9) might break down in some environments, and if so in which environments those might occur. Problematically, there are many of these assumptions that must be made to produce the comprehensive results being sought in this work. A careful reader will want each of these assumptions to be examined in depth, and some of that examination is included here. However, some of it is beyond the scope of this manuscript if it is to remain of reasonable length.

*We agree that assumptions need to be revisited in the text. See the Discussion section on lines 350-355 where we have restated some of our main assumptions with regard to the modeling analysis/decomposition process, and point out the importance of uncertainty in future studies.*

One of the strong points of the manuscript is the degree to which the probabilities of transitioning between wood classes are used as representations of the uncertainty in our understanding of what processes push material between classes. Some of this uncertainty comes from the discrepancy of estimates that come from using different quantification techniques. The authors make a strong effort to estimate the magnitude of this uncertainty through the markov modeling process. The net effect is improved clarity about the depth of our understanding of woody decomposition across species differences and broad geographical areas

One wonders about the degree to which these half-lives and residence times are altered in real forest situations because of physical tearing apart of the material by animals searching for insects to eat. Although such estimates are clearly outside the range of processes considered here, it would be fascinating to hear what these experienced authors have to say about the prevalence of this activity. I imagine that the transition probabilities estimated as part of the field data analysis take this process into consideration.

*Yes, we agree. Although the decay class designation system used in the present analysis does not specifically take into consideration damage/fragmentation from animals, such indicators of animal damage could be considered indirectly when designating decay class (e.g., whether the DWD piece is intact or not intact).*

The authors made a heroic effort to compare their estimates with other published in figure 3. It is very useful to see the variability in estimates different researchers have made, know how different methodologies and assumptions result in widely differing estimates.

Although these are clearly important ecosystems process issues being examined in this manuscript, the paper dives into the nuts and bolts of how one parameterizes, fits, and analyzes the results of a transition probability model. I wonder whether the typical reader of Ecosystems is prepared to delve this deeply into the modeling process, or whether this paper might be better served in Ecological Modeling.

*After considering this comment from the reviewer, we realized that the description and analysis of the former section labeled "Simulation Data" may be best served as supplementary material. Hence, Appendix A contains the text associated with (1) describing the collection of field data used in the simulation, (2) analytical assumptions related to assigning log length, and (3) results of equivalence tests between observed and predicted log length. We briefly mention this data and refer to Appendix A at the conclusion of the "Modeling DWD decay class transitions" section (line 160).*

*We hope that this change highlights the details needed to inform Ecosystems readers with additional information available for those readers interested in the specifics of the analysis. This change also shortens the manuscript quite a bit.*

Despite the concerns I have stated above, I want to make it clear that the results reported in the manuscript are useful estimates of the long term processes attempted to be captured. The assumptions on which these estimates are based are reasonable for the broad picture, and they are clearly stated. Consequently, they give us insight into the probable long term dynamics of woody debris, the temporal and geographical variability of these dynamics, and the magnitude of the influence of key environmental variables. Therefore, although the readers of this manuscript might get lost in the modeling specifics and might not completely appreciate the assumptions being made, they will not be greatly misled by trusting the decay estimates offered.

*Thank you for the encouraging comments. We hope that we have improved the presentation of this work for Ecosystems readers by outlining some of our key assumptions and reshaping how the Methods are presented.*

Specifics:
P. 15 line 30: It is not clear from figure 1 a-b that the conifer decay rate is nonlinear, as stated here.

*We have removed the reference to the "nonlinear" form.*

P. 34 Table 1 legend: Isn't this a summary of the field data of DWD employed in the simulation? The legend makes it sound like this is simulated data.

*Yes, this is a summary of the observed DWD data. (Changed).*

P. 38. Figure 3 legend: Either "T Half" should be outside the parentheses, or "k" should be inside the parentheses.

*We've moved k inside the parentheses.*

Figure 3 would be helped if, along with the respective reference, the species estimated in that reference, was listed on the key. The text on page 16 focuses on these species. It would be helpful if the manuscript discussed on page 18 why this study generally estimated longer times for T Half and lower values for k that the literature values.

*Text on lines 371-374 discusses differences in k compared to values reported in the literature. Unfortunately, given that multiple species are presented within several studies from the literature in Fig. 3, we feel it would be quite cumbersome to present species scientific names in the legend key. Instead, we invite the reader in the figure caption to consult the text for discussions of species-specific parameters found here to those reported in the literature.*

**In response to comments from Reviewer 2:**

Comments to the Author(s)
Residence time and rate of decay for downed woody debris biomass/carbon in eastern US forests
Russell and others

In this manuscript the authors present comprehensive research on downed woody debris biomass dynamics. The large dataset combined with a robust research approach yield a novel contribution to research on dynamics of downed woody debris dynamics, biomass and carbon flux. I believe this research is an important study that is worthy of publication in Ecosystems.

The reported dataset is impressive, generated from repeated sampling of forest inventory plots and includes a very large number of pieces of downed wood representing a broad range of species and forest types - 4,384 DWD pieces from 516 plots with a focus on 13 conifer and 23 hardwood species. This study illustrates the value of such large networks of permanent plots and the type of research problems that can be addressed using repeated-measures data.

The research approach appears robust. The authors combine empirical data on (a) woody debris attributes measured in permanent plots with (b) estimates of decreases in mass (density and volume) as wood decays in order to simulate wood transitions between decay classes and estimate rates of decay, biomass and carbon flux over time. The current study is a logical extension of the authors' recent publication "Estimates of coarse woody debris decay class transitions for forests across the eastern United States " in Ecological Modelling. In this manuscript, they build on their decay class transition model by deriving half-life (THALF), residence time (TRES), and decay rate (k constants) for downed wood, reporting rates for different species and climate regions. They derive plot-level changes in biomass and carbon flux through time. By comparing multiple forests distributed along climatic gradients, their work provides insight into the effects of climate on these processes.

The interpretation of the results is clear and concise; discussion and conclusions are well supported by the cited literature.

Overall, the manuscript is logically organized and clearly written. I have a few minor editorial suggestions, provided below.

*We thank the reviewer for the helpful feedback. We agree that the analysis could not have been possible without the breadth of information collected across the network of Forest Inventory and Analysis plots.*

Keywords – Omit bioenergy – it is not a core concept in the paper, but of several applications mentioned in the introduction and discussion

*Omitted "bioenergy".*

P8 L18-27 It is not clear how 2 x 18-m transects per subplot ultimately yield 143.6m per plot. How many subplots are there per plot? Why isn't the total length a multiple of 18?

"Individual DWD pieces were sampled using a line-intercept sampling method (VanWagner, 1968) on 18.0-m (58.9-ft) horizontal distance transects radiating from each FIA subplot center at azimuths of 30, 150, or 270 degrees. Only two transects from the three azimuths were sampled within each subplot depending on spatial arrangement, totaling 143.6 m for an entire inventory plot."

*We have clarified that four FIA subplots were used which total 143.6 m in Appendix A on line 13, e.g., 2*18*4.*

P8 L44 – P9 L30 I had to read this section a few times to understand what was done and why. It seems you are justifying the "start point" for your simulation. Assuming I have understood properly, I am ok with this approach; however this point was not clear until I had read the entire paragraph. A different lead sentence needed to introduce and justify this simulation. I suggest focussing on the objective and approach rather than the underlying (unrealistic) assumption that is being tested.

Specifically, the current lead sentence includes an assumption that is hard to justify without more context: "For the purposes of simulating DC dynamics of the DWD population measured in 2001, we considered all DWD pieces to be non-decayed." Instead, the second last sentence hints at the actual purpose of this analysis: "setting length equal to the observed length measured in 2001 was appropriate to initiate the simulation".

As well, clarification is needed in the following sentence (P8 L53-P9 L4): "Hence, we tested for differences in observed length (i.e., the 2001 measurement) and predicted length assuming a DC 1 using an equation form that used DC, DIASM and DIALG as independent variables (Woodall et al., 2008)" Do you mean you assumed the wood was in decay class 1 and applied the Woodall equation, even if the wood was in decay classes 2-5?

*We have rewritten this paragraph to be succinct and clear (Appendix A; first paragraph). At the outset of the paragraph, we outline our objective in assessing alternative aspects related to DWD length: "Assigning a length to the DWD pieces to initiate the simulation required the testing of some important assumptions related to log decay". We hope this places this section of the methods in a better context. We clarify that we test differences in observed length and predicted length (assuming a DC of 1 but all other variables [e.g., large-, small-end diameters] equal to their observed values).*

P11 L20-22 Lead sentence not clear: "Simulating the DWD data using the DC transition models allowed us to approximate the number of years in which the proportion of biomass remaining attained any specified proportion" Two corrections are needed: (1) The DWD data were not simulated, rather the data and models were used to simulate… (2) The second half of the sentence seems to mix the objective (biomass in different classes?)

and the criterion (number of years to deplete to a specified level?) for determining if the objective was met. Perhaps simplify to a strong lead sentence followed by a second statement on the criterion. Also see next comment.

P11 L20 - P12 L32 The concluding sentence of this section is: "In summary, three key metrics of DWD biomass loss were assessed: (1) THALF, (2) TLIBRES, and (3) TCONRES". This purpose was not immediately clear to me – after reading this sentence I traced back through the text to verify that this was the main message of the previous paragraphs. As noted above modifying the lead sentence at the start of the section will help to clarify this intent. At the start, I suggest stating this as well – eg. lead sentence on P11 L20 could read: The DWD data and DC transition models were used in a simulation to quantify three metrics of biomass loss, DWD half-life and two measures of residence time.

*We agree that the suggested text change results in a better understanding of the paragraph and incorporated it into this version (lines 203-205).*

P13 L41-48 Clarify that there were four subplots = 3 x 7.32 x 4 = 87.8m
"These data were collected in a similar manner to the 2001 data, with the primary difference being that DWD were sampled along three 7.32-m transects at each of four subplots, totaling 87.8 m for a complete FIA plot."

*We added "at each of four subplots" for clarification (line 259).*

Table 1 – Restructure so that the information on the number of species is in the table caption and the sample sizes are given in the left column with the categories plots and DWD pieces. The current format is difficult to follow, since the flow of the vertical columns in interrupted by information relevant to the rows than columns.

*Thanks for the helpful suggestion. We've done just that.*

# Residence time and decay rates of downed woody debris biomass/carbon in eastern US forests

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**Keywords**: carbon flux, decomposition, forest inventory, forest fuels, decay class, coarse woody debris



[1] Author contributions: MBR, CWW, SF, and AWD designed the study and performed the research; MBR analyzed data and contributed new methods; all authors discussed the results of the study and contributed to writing the manuscript

**Abstract**

A key component in describing forest carbon (C) dynamics is the change in downed dead wood biomass through time. Specifically, there is a dearth of information regarding the residence time of downed woody debris (DWD), which may be reflected in the diversity of wood (e.g., species, size, and stage of decay) and site attributes (e.g., climate) across the region. The empirical assessment of DWD rate of decay and residence time is complicated by the decay process itself, as decomposing logs undergo not only a reduction in wood density over time, but also reductions in biomass, shape, and size. Using DWD repeated measurements coupled with models to estimate durations in various stages of decay, estimates of DWD half-life ($T_{\mathrm{HALF}}$), residence time ($T_{\mathrm{RES}}$), and decay rate ($k$ constants) were developed for 36 tree species common to eastern US forests. Results indicate that estimates for $T_{\mathrm{HALF}}$ averaged 18 and 10 years for conifers and hardwoods, respectively. Species that exhibited shorter $T_{\mathrm{HALF}}$ tended to display a shorter $T_{\mathrm{RES}}$ and larger $k$ constants. Averages of $T_{\mathrm{RES}}$ ranged from 57 to 124 years for conifers and from 46 to 71 years for hardwoods, depending on the species and methodology for estimating DWD decomposition considered. Decay rate constants ($k$) increased with increasing temperature of climate zones and ranged from 0.024 to 0.040 for conifers and from 0.043 to 0.064 for hardwoods. These estimates could be incorporated into dynamic global vegetation models to elucidate the role of DWD in forest C dynamics.



**Introduction**

Forest ecosystems and their associated carbon (C) stocks have become an important consideration of global strategies aimed at reducing greenhouse gas (GHG) concentrations and possibly mitigating future climate change effects (Ryan et al. 2010, Malmsheimer et al., 2011; McKinley et al., 2011). An important component of forest C is dead wood, of which a major component is downed woody debris (DWD; defined hereafter as downed dead wood ≥ 7.62 cm in diameter and ≥ 0.91 m in length). This DWD may be a large component of overall stocks, accounting for ca. 20% of total C in primary (i.e., old growth; Harmon et al., 1990) and secondary (Bradford et al., 2009) forests.

The decomposition of DWD has emerged as a knowledge gap hampering our ability to quantify changes in C pools (Birdsey et al., 2006). Improved estimates of DWD decay rates have a direct use in process-based (e.g., Aber et al., 1995) and empirical (e.g., Rebain et al., 2010) ecosystem dynamic models, while a refined understanding of the DWD decay process has important implications for forecasting forest fuel loads (Rollins et al., 2004), assessing potential habitat for dead wood-dependent organisms (Stokland et al., 2012), and addressing the implications of utilization of logging slash for bioenergy production (e.g., forest harvest residues) on C balances and net GHG emissions (Schlamadinger et al. 1995, Sathre and Gustavsson 2011, Zanchi et al., 2012). By coupling estimates of DWD decay with climate information, it may be possible to estimate changes in DWD decomposition rates under future climate scenarios. Ultimately, a clearer understanding of the variability of DWD decay rate and associated C flux estimates is essential for predicting ecosystem responses to global change (Weedon et al., 2009).

Methodologies for sampling and quantifying the volume, biomass, and C content of DWD and their associated stocking levels have greatly improved in recent years (Fraver et al. 2007, Woodall et al. 2009, Gove and Van Deusen 2011, Fraver et al. 2013; Gove et al., 2012, Ritter and Saborowski 2012). However, studies that investigate the temporal dynamics of DWD are limited, yet urgently needed to determine the role of woody forest detritus in regional C cycles. Specifically, few studies have quantified DWD mass loss through time. Most studies that investigate DWD decay rates estimate changes in wood density, which is often used as a surrogate for mass. As an example, of the 37 studies reviewed by Laiho and Prescott (2004; their Table 4), only five addressed DWD mass loss; the remainder focused on density depletion. However, the use of density depletion is known to underestimate mass loss because it fails to consider log volume loss as decay progresses (Harmon et al. 1987, Næsset, 1999, Zell et al. 2009, Fraver et al. 2013).

In routine DWD inventories in the US, a five-class system is commonly used to denote the decay class (DC) of individual DWD pieces (Woodall and Monleon, 2008), based on physical characteristics of the piece. Obtained through a synthesis of North American DWD density data, the ratio of the density of a decayed DWD piece to that of a nondecayed piece, termed a DC reduction factor (Harmon et al., 2011), can be used to estimate density reduction that occurs as pieces advance through subsequent DCs. Because estimates of DWD mass based on density alone will underestimate mass loss (as above), additional reduction factors can subsequently be incorporated to account for DWD structural changes (i.e., volume loss) as decay progresses (e.g., Means et al., 1985; Spies et al., 1988, Fraver and Palik 2012), an approach that has recently been applied to standing dead wood (Domke et al., 2011).

For studies that have meticulously measured C flux on decaying DWD, methodologies have been restricted to logs of intermediate decay. For example, DC 2 pieces were only investigated by Hagemann et al. (2010), while Noormets et al. (2012) examined DC 2 and 3 pieces. Stage of decay has been shown to influence DWD C flux (Wang et al., 2002), hence, including pieces in all stages of decay is essential to accurately depict DWD mass loss dynamics. Chronosequence studies have been used as one approach to capture these dynamics over a range of decay classes (e.g., Mattson et al. 1987, Mackensen and Bauhus 2003, Noormets et al., 2012);

however, the time and effort required for such studies has generally restricted their application to a specific forest type under a controlled set of stand conditions. Given the limitations to these various approaches, the use of decay class simulations could be a powerful alternative for estimating mass loss rates of DWD. Using a DC transition model (e.g., Kruys et al., 2002, Aakala 2010, Russell et al. 2013), simulations allow one to quantify the degree of uncertainty surrounding estimates of DWD mass loss. By quantifying uncertainty attributed to both model performance and inventory measurements, confidence intervals can be constructed to assist in our understanding of DWD mass-loss dynamics. Given the various decomposition pathways and factors influencing wood degradation (Stokland et al., 2012), simulation-based models aimed at accurately estimating DWD decomposition at large regional scales need to account for species and forest type differences, climatic regimes, and DWD physical attributes such as decay class and piece size.

As a quantitative measure of decay rates, investigators have defined DWD half-life to be the number of years for a DWD piece of a specific size to lose 50% of its initial biomass. As an example, Radtke et al. (2009) reported DWD half-lives to range between five and eight years for *Pinus taeda* L. in southeastern US plantations. In contrast, measures of DWD residence time are much more multifaceted and have been given several definitions. Early estimates for DWD residence time assumed a linear decay of woody debris over a 10-year period (IPCC 1997), a model form and default value which was found to be a tremendous overestimate of DWD decomposition for common species in southeastern Australia (Mackensen et al., 2003). Some define DWD residence time as the number of years in which 10% (Hérault et al., 2010), 5% (Mackensen and Bauhus, 2003), or 1% (Lambert et al., 1980) of initial DWD biomass remains, while others approximate DWD residence times based on experimental observations (Mackensen et al., 2003).

The primary goal of this study was to estimate the decay rate and residence time of DWD across the major forest types of the eastern US using Forest Inventory and Analysis data. Specific objectives were to: (1) estimate DWD biomass depletion through time by coupling DC transition simulations with associated DC and volume reduction factors and (2) quantify DWD decay rate, half-life, and, residence time for the primary species and associated DWD C flux for common forest types in the eastern US. A Monte Carlo-based simulation approach was used to determine the effectiveness of estimating DWD residence time for individual species to address questions regarding C accounting.

**Methods**

*Study area*

Forest types of the eastern US are diverse, ranging from hemlock-pine-northern hardwood (north), oak-hickory (west), and southern pine forests (south and east) (Smith et al., 2009). The study area investigated here ranged eastward from the state of Minnesota to Maine in the north and Louisiana and Georgia in the south, spanning approximately 18 degrees latitude and 29 degrees longitude. Whether observing the Köppen climate regions (Kottek et al., 2006) or Bailey (1980) ecoregions, each forest type varies in terms of its potential productivity and species assemblage. Across the study area, mean annual temperatures (MAT) range from 1.4 to 19.8° C and precipitation from 55 to 201 cm (Rehfeldt 2006, USFS 2012 ). More than 75 forest types have been identified by the USDA Forest Service's Forest Inventory and Analysis (FIA) program across the study area, which represent 14 broader forest type groups (Woudenberg et al., 2010).

*Modeling DWD decay class transitions*

During field inventories, DC was assigned to each DWD piece using a five-class system, with 1 being least and 5 being most decayed. Estimates of DWD DC transition, defined as the probability that a DWD piece will remain in the same DC or advance to subsequent DCs in five years, have recently been quantified across the eastern US (Russell et al., 2013). Downed woody debris DC transitions were estimated by predicting the cumulative probabilities of pieces advancing in decay using a cumulative link mixed model (Russell et al. 2013; using matched data [their Table 3]) with forest type (ForType) specified as the random effect. As DWD C loss is likely linked to its unique attributes and endemic climate (Herrmann and Bauhus, 2013), the number of degree days greater than 5° C (DD5), coupled with the length of the DWD piece (LEN; m) and initial DC, were used to indicate decomposition potential across the eastern US and thus estimate DWD DC transitions (Russell et al., 2013):

$$\mathrm{logit}(\gamma_{ikj}) = \theta_k - \beta_1\,\mathrm{DD5} - \beta_2\,\mathrm{LEN} - u\mathrm{ForType}_j + \varepsilon \quad (1)$$

where $\theta_k$ is the intercept term for DC $k$ (i.e., DC 1, DC 2, DC 3, DC 4, or DC 5), $\gamma$ is the cumulative probability for DWD piece $i$ moving through each of the successive $k$ decay classes within each ForType $j$, $\beta_i$ are the parameters estimated for conifer and hardwood species separately, and $\varepsilon$ is the random residual term. The random effect $u$ was specified to represent forest type-specific effects on the transition process. Models were fit using paired DWD piece observations (measured once between 2002-2007, then remeasured 5 years later) from a national forest inventory database (FIA) of eastern US forests (Woodall et al., 2012). Other variables representing climate, including mean annual precipitation did not reduce Akaike's information criteria and log-likelihood statistics (Russell et al., 2013). The data used for simulation in this analysis was a DWD inventory collected across 23 eastern US states in 2001 and are independent of datasets used in related studies (Table 1; Appendix A; Woodall et al., 2012; Russell et al., 2013).

*Monte Carlo simulations of DWD decay*

As DWD DC transition models predict the five-year probability of remaining in the same DC or advancing to subsequent DCs, we used a DC reduction factor (DCRF; Harmon et al., 2011) to estimate changes in DWD wood density through time. Recognizing that employing the DCRF alone may underestimate the true rate of mass loss (Harmon et al., 1987, Zell et al. 2009, Fraver et al. 2013), we similarly incorporated the DCRF with a volume reduction factor (VRF) to account for structural reductions in DWD volume as decay progresses. We applied a VRF of 0.800 and 0.412 for DC 4 and 5 pieces, respectively, to all species as observed by Fraver et al. (2013) for three species in Minnesota. As no difference was observed in VRFs for hardwood and conifer species (Fraver et al., 2002), and others have observed similar VRF values in contrasting forest types (e.g., 0.439 and 0.431 for DC 5 pieces observed by Spies et al. [1988] and Means et al. [1985], respectively, in *Pseudotsuga menziesii* Mirb. Franco logs; and 0.82 and 0.42 for DC 4 and 5 pieces, respectively for *Pinus* species in Minnesota [(Fraver and Palik 2012]), we assumed the VRFs chosen would have wide applicability for species across the eastern US. Hence, estimates of DC transition and ultimately DWD biomass represented decay estimated from both density and volume reduction, thus providing a realistic assessment of mass depletion.

Predictions were accomplished by applying the DWD DC transition equations (Russell et al., 2013; fixed-effects only) to the 2001 data described above using a Monte Carlo simulation framework, as follows. First, the independent variables DD5 and LEN were used to represent climate regime of the plot location and DWD piece size, respectively, and were subsequently applied to estimate the DWD DC transition. Then, a random number was drawn from a uniform probability density function $U$~(0,1) and compared with the cumulative five-year probability predicted using the DC transition model. If the random number was less than or equal to the predicted probability of remaining in the same DC, it remained in the same class. If the random number fell between the predicted probability of remaining in the same DC and the cumulative probability of remaining in the same DC or advancing one DC, it advanced one class. Similarly, if the random number fell between the predicted probability of remaining in the same DC and the cumulative probability of remaining in the same DC, advancing one DC, or advancing two DCs, it advanced two classes (e.g., from DC 1 to 3), and so on (Appendix B). Equations provided predictions in five-year increments, and simulations were applied iteratively until all DWD pieces reached DC 5. For each of the 4,384 DWD pieces, a 1,000-run Monte Carlo simulation was performed up to 200 years.

The volume (*Vol*) and biomass (*Mass*) were computed for all DWD pieces at each five-year step. DWD *Vol* was estimated assuming a conic-paraboloid form (Fraver et al., 2007). Initial density (*ID*; kg $m^{-3}$) for an individual species $m$ (Harmon et al., 2008), the appropriate DCRF for DWD of a given species group $n$ in a DC $k$ (Harmon et al., 2011; Table 6), and the appropriate VRF for DC $k$ was multiplied by *Vol* to estimate *Mass*:

$$Mass = ID_m * DCRF_{kn} * VRF_k * Vol \quad (2)$$

where VRF is 1, 1, 1, 0.800, and 0.412 for DC 1, 2, 3, 4, and 5, respectively. The proportion of biomass remaining compared to initial (i.e., non-decayed) biomass, denoted as $Mass_{(R)}$, was estimated at each five-year step.

The DWD data and DC transition models were used in a simulation to quantify three measures of biomass loss: DWD half-life and two measures of residence time (one liberal and one conservative estimate). We considered the number of years when the mean value of $Mass_{(R)}$

for a species group of interest reached 0.50 as the DWD half-life, denoted $T_{HALF}$. Determining DWD residence time was more complex, as the process represents a gradual transition and is not necessarily marked by a distinct end point (Mackensen and Bauhus, 2003). We determined DWD residence time using an empirical assessment of the reduction factors involved for a DC 5 piece, as follows. After an algebraic manipulation of Eq. 2, one will notice that *Mass* will reach a lower asymptote at the minimum value for its DCRF. This value is 0.29 and 0.22 for DWD pieces of DC 5 for conifer and hardwood species, respectively (Harmon et al., 2011; Table 6). However, if the statistical variability presented in these DCRF values are considered (Harmon et al., 2011), these same values are 0.29±0.02 (mean ± two standard errors) and 0.22±0.04, respectively. One also needs to consider the variability surrounding the *VRF* for a DC 5 piece, which is 0.412±0.172 (mean±SD; Fraver et al., 2013). If the statistical variability presented in both the *DCRF* and *VRF* are computed, the lower asymptote values for *Mass* are 0.119±0.100 (mean ± two standard errors) and 0.091±0.078, for conifers and hardwoods, respectively, after computing the variance of the product of two random variables.

Hereafter, we define a liberal estimate of DWD residence time ($T_{LIBRES}$) as the number of years in which the mean proportion of biomass remaining for all DWD pieces falls within two standard errors of the mean for a DC 5 piece. Similarly, we define a conservative estimate of DWD residence time ($T_{CONRES}$) as the number of years in which the mean proportion of biomass remaining for all DWD pieces falls within one standard error of the mean for a DC 5 log. From a biological perspective, these residence times might be used as a surrogate for the number of years until a DWD piece loses all structural integrity and transitions to another population (i.e., another carbon pool). At this point, the DWD piece may be incorporated into the soil organic horizon and thus no longer meets the criteria for being inventoried as DWD (exclusive of combustion or harvest removal). In summary, three key metrics of DWD biomass loss were assessed: (1) $T_{\mathrm{HALF}}$, (2) $T_{\mathrm{LIBRES}}$, and (3) $T_{\mathrm{CONRES}}$.

Means and standard deviations of $Mass_{(\mathrm{R})}$ at each five-year step were summarized from the simulation results for (1) all conifer and hardwood DWD pieces, (2) DWD pieces by DWD length (i.e., short, medium, and long pieces), and (3) DWD pieces by $\mathrm{DIA_{LG}}$ classes (i.e., small, medium, and large pieces). Based on the means estimated for $Mass_{(\mathrm{R})}$, inverse linear interpolation was used to approximate the number of years that $T_{\mathrm{HALF}}$, $T_{\mathrm{LIBRES}}$, and $T_{\mathrm{CONRES}}$ were attained.

Finally, we used these simulation results to calculate decay rates for the species and climate regions of interest. The annual rate of decomposition was determined using the negative exponential model (Olson, 1963) to supplement the developed half-lives and residence times. Here, the annual decay rate parameter $k$ was obtained from $Mass_t = Mass_0\exp(-kt)$, where $Mass_t$ is DWD biomass at time $t$ (years) and $Mass_0$ is initial biomass. Summaries were made for conifers and hardwoods grouped according to MAT of plot location and for individual species that contained 20 or more observations.

*Comparisons with published estimates*

We compared our estimates of $T_{\mathrm{HALF}}$ and $k$ for several species with previous investigations that estimated similar DWD attributes using chronosequence and/or direct studies primarily through the use of density-loss curves. To validate the predictions from our simulation approach to previous empirical studies, the percentage of predictions accurate to within ± 50% of reported estimates (Rykiel, 1996) was calculated for all species and/or where DWD half-lives and $k$ parameters were reported. The ± 50% value was chosen because of the tremendous variability in how these studies estimate decay parameters (e.g., chronosequence versus direct measurements; density- versus mass-loss curves).

*Ecosystem-level C flux*

To investigate the performance of our simulation approach and associated estimates of DWD decay rates and residence times, we forecasted ecosystem-level DWD C estimates. This was accomplished by projecting current DWD stocks inventoried from 2007-2011 (hereafter termed "year 2010") by the FIA program in 29 eastern US states (Woodall et al., 2013). These data were collected in a similar manner to the 2001 data, with the primary difference being that DWD were sampled along three 7.32-m transects at each of four subplots, totaling 87.8 m for a complete FIA plot (Woodall and Monleon, 2008).

Current DWD C stocks were first estimated by multiplying plot-level biomass values by a C concentration constant of 0.5 (Mg/ha), followed by a simulation of DWD pieces. Carbon stocks in the DWD pool were then estimated in 5-year time steps from 2010 onward. Assuming no inputs into the DWD pools over a 100-year span, C flux was defined as the amount of C lost for each 5-year span (Mg/ha/5-yr). If the estimate of $T_{CONRES}$ (i.e., the conservative DWD residence time) for a given species was exceeded by the number of simulation years, then it was assumed that the piece had completely decomposed (i.e., biomass was set equal to zero). Means for C flux were summarized by forest type group following multiple simulation runs.

**Results**

*Monte Carlo simulations of DWD decay*

For the 32 conifer species in this study's simulation dataset, mean $DIA_{LG}$ and LEN averaged 17.9 ± 8.2 cm and 7.9 ± 5.9 m (mean ± SD), respectively, on 275 inventoried plots. For the 87 hardwood species, these same attributes measured on 454 plots averaged 18.4 ± 10.0 cm and 6.0 ± 4.8 m, respectively (Table 1).

Based on the proportions of biomass remaining for all DWD pieces, conifers exhibited relatively slow decay, while hardwoods displayed a rapid decay to their observed $T_{HALF}$ (Figure 1a-b). Estimates of DWD half-lives and residence times were shorter as MAT increased, which was observed along with an increase in the decay rate parameter $k$ (Table 2; Appendix C). Values for the decay rate parameter $k$ ranged from 0.024 for conifers in the coolest climate zones (MAT < 2.8 °C) to 0.064 for hardwoods in the warmest climate zones (MAT > 13.7 °C). Estimates of $T_{HALF}$ averaged 18 and 10 years for conifers and hardwoods, respectively. For conifers, estimates of $T_{HALF}$ ranged from 12 years for *Pinus elliottii* Engelm. to 22 years for *Pinus banksiana* Lamb. For hardwoods, $T_{HALF}$ ranged from 8 years for two species in the *Quercus* genus and *Liquidambar styracifula* L. to 11 years for two species in each of the *Betula* and *Populus* genera and *Fraxinus nigra* Marsh. Similar trends were evident in decay rates: values for the decay rate parameter $k$ ranged from 0.023 to 0.048 and from 0.043 to 0.076 for conifers and hardwoods, respectively (Table 3; Appendix D).

Estimates of $T_{CONRES}$ averaged 80 and 69 years for conifer and hardwood species, respectively. Species with short half-lives tended to display short residence times, with some exceptions (Table 3). For example, *Prunus serotina* Ehrh. and *Quercus prinus* L. displayed estimates for $T_{HALF} \leq 10$ years, yet showed some of the longest residence times among the hardwood species examined (≥ 63 years when considering $T_{CONRES}$). Relative to DWD residence time (as measured by $T_{CONRES}$), $T_{HALF}$ occurred at approximately the 25$^{st}$ and 15$^{th}$ percentiles for conifers and hardwoods, respectively, indicating that hardwoods took relatively longer to reach residence time after achieving their initial 50% mass loss.

Differences in estimates of half-lives and residence times were noted when DWD pieces were analyzed across three corresponding length classes (Figure 2a-f). For example, $T_{\mathrm{HALF}}$ for *Abies balsamea* (L.) Mill. pieces was predicted to be 23, 24, and 27 years for short, medium, and long DWD pieces, respectively. Similar relationships were observed when pieces were analyzed across three corresponding $\mathrm{DIA}_{\mathrm{LG}}$ classes.

*Comparisons with published estimates*

Eighty percent of the species- or genus-specific estimates for $T_{\mathrm{HALF}}$ reported here were within ± 50% of the half-lives reported for the same species in other studies found across eastern US states (Figure 3a). Estimates were most similar for *Picea rubens* Sarg. (Foster and Lang, 1982) in New Hampshire and *Pinus resinosa* Ait. in Minnesota (Fraver et al., 2013), each which displayed a $T_{\mathrm{HALF}}$ within ±5%. The largest percent difference in reported estimates for $T_{\mathrm{HALF}}$ was for *Pinus taeda* (Mobley et al., 2013) and *Quercus* spp. (MacMillan, 1988). Similarly, 42% of the species- or genus-specific estimates for the decay rate parameter *k* reported here were within ± 50% of the values for *k* reported for the same species in other studies (Figure 3b).

*Ecosystem-level C flux*

Generally, hardwood-dominated and mixed forest types experienced higher initial rates of DWD C flux than conifer-dominated ecosystems (e.g., the first 10 years; Figure 4a-c). Although oak-gum-cypress forest types had the largest current DWD stocking levels (1.78±3.46 Mg C/ha), DWD stocks on these plots were projected to deplete the fastest assuming no future inputs. Current DWD C stocks were forecasted to undergo 99%-depletion in 80 years for plots found in white-red-jack pine, spruce-fir, and aspen-birch forest type groups (the maxima observed) and in 53 years for loblolly-shortleaf pine forest types (the minimum observed).

## Discussion

*DWD decay rates*

The Monte Carlo simulation approach served as a viable tool to test the validity of the probability-based DC transition model to characterize DWD biomass dynamics through time. Methods outlined here generated estimates of DWD decay rate, half-life, and residence time that are biologically-reasonable based on comparisons to published estimates for common species found in eastern US forests. The approach presented here could be applied to any DWD inventory with repeated measurements, including national forest inventories, to produce decay rates, half-lives, and residence times for a wide range of species and forest types. As such, our approach has direct implications for tasks such as refining dead wood C flux rates in forest ecosystem models (Aber et al., 1995), forecasting forest fuel loads (Rollins et al., 2004), assessing habitat dynamics for dead wood-dependent organisms (Stokland et al., 2012), understanding the role of forest residue in a C accounting framework, and informing forest bioenergy policies. Moisture, temperature, C concentration, forest floor contact, and composition of the decomposer fungal community all influence DWD decomposition rates (Harmon et al., 1986, Stokland et al. 2012; Harmon et al., 2013), but are not necessarily measurements influencing residence time as defined here. To refine conversions of DWD volume into biomass and C, estimates of DWD stocks can likely be improved by investigating the assumption of 50% C content. For example, Weggler et al. (2012) observed that default values for C concentrations overestimated DWD C when compared to species-specific C concentrations for common species in Switzerland, and Lamlom and Savidge (2003) concluded that C content varied substantially within individual trees and across species, including many of the species analyzed in this study. Harmon et al. (2013) suggest that the C content of recalcitrant DWD components (e.g., lignin) varies through the decay process in concert with differences in fungal colonization, thus increasing the complexity of modeling such systems. Incorporating these ecological factors and seeking improvements in volume-to-biomass-to carbon conversion factors, through detailed measurements at experimental sites, could help to refine mass/C loss estimates within a given forest type and/or at regional scales.

As suggested by Harmon et al. (2011), the methodologies that rely on density-loss estimates alone should serve only as a preliminary assessment for analyses that quantify DWD decay processes. We suggest that the density- plus structural-loss approach applied here provides a more realistic assessment of mass loss through decay, as it avoids the underestimation inherent in the commonly-used density-only approach. Nevertheless, it is important to note the various assumptions involved in implementing this approach, including applying VRFs to all species across the region, using fixed C concentration and initial density values, and accepting the idea that DC transition models can be used to infer decomposition parameters (e.g., $k$). Future studies that examine the uncertainty associated with these assumptions should refine our understanding of DWD decomposition temporal dynamics.

*Comparisons with published estimates*

Despite the variability across studies and different-sized DWD pieces examined, 80% of the estimates for $T_{\mathrm{HALF}}$ reported here were within ± 50% of the half-lives reported for the same species in other studies. For example, Lambert et al. (1980) observed a half-life for *Abies balsamea* logs of 23 years, while we found a $T_{\mathrm{HALF}}$ of 20 years. In the US southern Appalachian region, Harmon (1982) found the following three species to decay fastest to slowest: *Quercus prinus* > *Acer rubrum* L. > *Pinus virginiana* Mill., and we similarly observed these species to decay from fastest to slowest when considering $T_{\mathrm{HALF}}$. Through direct measurements, Alban and Pastor (1993) found that species that decayed fastest at two sites in Minnesota were in the order of *Populus tremuloides* Michx. > *Picea glauca* (Moench) Voss > *Pinus resinosa* > *Pinus banksiana*, which we also observed, although estimates of $T_{\mathrm{HALF}}$ were approximately equal for *P. glauca* and *P. resinosa*. The largest discrepancy for a hardwood species was between our estimates for *Quercus* spp. (approximately 9 years) and the value reported by MacMillan (1988; 40 years). This difference likely arises because of the relatively large diameter logs (mean of 36 cm) sampled by MacMillan (1988), when compared to ours (mean of 18 cm), assuming that large diameter logs decay more slowly (Harmon et al., 1987). Values for the *k* parameters calculated here generally were less than those reported in the literature (Figure 3b), which could be related to differences among studies that solely use mass loss to estimate decomposition or from our sample containing larger-diameter DWD from the FIA inventory (> 7.6 cm). We hesitate to make similar quantitative estimates of $T_{\mathrm{LIBRES}}$ and $T_{\mathrm{CONRES}}$ with other studies due to the large variability in how DWD residence time is defined across studies. For example, the number of years it takes for 95% of DWD to decompose is commonly reported (e.g., Alban and Pastor 1993, Mackensen and Bauhus 2003) and could be considered a metric of DWD residence time. Common to many of these studies is the use of a density depletion curve fitted using the negative exponential model, but this may not appropriately account for lags in decomposition, water-logged pieces, and/or may contain decay-resistant wood (Harmon et al. 2000, Hérault et al., 2010, Fraver et al. 2013). Similarly, if structural losses are not taken into account for DWD in advanced stages of decay, studies may overestimate the true biomass and C content of DWD. Despite the differences in definitions of DWD residence time and difficulties in quantifying biomass at advanced stages of decay, the $T_{\mathrm{LIBRES}}$ and $T_{\mathrm{CONRES}}$ estimates reported here provide a limited range of DWD residence times for the common species in the eastern US. Results indicate that estimates of DWD residence time could range from as rapid as 44 years for short (<

3.9 m) *Acer rubrum* logs to as extensive as 161 years for long *Abies balsamea* (>7.6 m) and *Pinus banksiana* (> 14.0 m) logs.

Similar estimates were obtained when pieces were analyzed across three corresponding $DIA_{LG}$ classes, indicating that measures of DWD length may be equally beneficial to estimating DWD decomposition as diameter. Although some studies have found diameter to influence the decay rate of DWD (Mackensen et al., 2003; Zell et al., 2009), others have not (Harmon et al., 1987; Radtke et al., 2009). The finding that DWD half-lives and residence times were similar whether using length or diameter is important for two primary reasons. First, not all inventories measure end diameters, especially in line-intercept sampling, however, DWD piece length is routinely collected (Woodall et al., 2008). Second, DWD length reflects the degree of nonfragmentation and soundness of pieces in all stages of decay, whereas long-axis diameter measurements will overestimate volume for DWD in advanced decay stages (Fraver et al., 2007).

*Ecosystem-level C flux*

Through predicting the decay dynamics of individual pieces, stand-level DWD stocks can be projected. This analysis demonstrated such an approach for projecting C flux rates into the future. The fact that oak-gum-cypress and oak-hickory forests displayed some of the highest rates of DWD C flux was not surprising given that those forest types are located at lower latitudes with warm climates and are dominated by hardwoods that display short residence times. Using the eastern US as a study area, our estimates of short residence times for hardwoods agrees with others that have found conifers to decompose more slowly than hardwoods (Weedon et al., 2009). It is important to note that we did not account for future DWD inputs in these simulations; however, future work coupling our simulation approach with ecosystem simulation and dynamic global vegetation models could allow for an array of C flux projections. Given the importance of climate in DWD DC transition models, such projections could also be designed to account for the influence of future climate regimes on DWD dynamics.

*Conclusions and management implications*

The approach outlined has the ability to quantify a variety of ecosystem functions related to forest detritus. For example, our estimates of DWD residence time can directly inform the question as to how long delineated populations of DWD are expected to reside in forest ecosystems. This could help in quantifying C stocks for future climate scenarios (e.g., Aber et al., 1995) and can aid in estimating net GHG emissions over time associated with burning of logging slash for energy (e.g., Schlamadinger et al., 1995; Sathre and Gustavsson, 2011; Zanchi et al., 2012). Values presented for the decay rate parameter $k$ could be used as parameters in forest ecosystem models of various scales and resolutions, including empirical (e.g., the Fire and Fuels Extension to the Forest Vegetation Simulator [Rebain et al. 2010]), process-based (e.g., CENTURY [Kirschbaum and Paul 2002], CenW [Kirschbaum 1999], and BIOME-BGC [White et al. 2002)] and dynamic global vegetation models such as LPJ (Sitch et al., 2003) to represent decomposition rates of plant material.

The rates of DWD C depletion presented here could be used as a benchmark when quantifying the influence of alternative climate scenarios on DWD decay processes. Similar estimation techniques that quantify the C implications of contrasting emissions scenarios with those that are focused on forest-derived biomass are only allowable through regional-scale analyses such as those presented here. Estimates of DWD half-lives, residence times, and decay rates can similarly serve as a baseline for assessing future forest ecosystem responses to global changes.

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**Supplemental material**

**Appendix A** Description of data used for simulation of decay class transitions across the eastern US.

**Appendix B** R scripts for estimating downed woody debris decay class transitions.

**Appendix C** Decay rate constants *k* predicting the annual decomposition of conifers and hardwoods located in four contrasting climate regimes, grouped by their mean annual temperature (MAT; °C). Curves displayed assume a 100-kg downed woody debris piece.

**Appendix D** Decay rate constants *k* predicting the annual decomposition for selected species. Species displayed are for the minimum, mode, and maximum *k* values observed for conifers (black) and hardwoods (gray) assuming a 100-kg downed woody debris piece.

**Table legends**

**Table 1** Summary of downed woody debris (DWD) data employed in this analysis collected by the US Forest Inventory and Analysis program across 23 eastern US states in 2001, for conifer ($n$ = 32) and hardwood species ($n$ = 87).

**Table 2** Estimates of downed woody debris half-life ($T_{HALF}$), liberal ($T_{LIBRES}$) and conservative ($T_{CONRES}$) residence time (years), and associated decay rates ($k$; standard errors in parentheses) predicting the annual decomposition for conifer and hardwood species groups found in eastern US forests by climate regime.

**Table 3** Estimates of downed woody debris half-life ($T_{HALF}$), liberal ($T_{LIBRES}$) and conservative ($T_{CONRES}$) residence time (years), and associated decay rates ($k$) predicting the annual decomposition for common conifer and hardwood species found in eastern US forests.

**Table 1**

| | Variable † | Mean | SD | Min | Max |
|---|---|---|---|---|---|
| | Conifers | | | | |
| Plot ‡ ($n$ = 275) | DD5 (> 5° C) [b] | 2861.8 | 1331.2 | 1233.0 | 5669.0 |
| | MAT (° C) | 9.7 | 6.3 | 1.5 | 20.6 |
| DWD piece ($n$ = 2,138) | $DIA_{SM}$ (cm) | 9.9 | 4.6 | 7.6 | 76.2 |
| | $DIA_{LG}$ (cm) | 17.9 | 8.2 | 7.6 | 101.6 |
| | LEN (m) | 7.9 | 5.9 | 0.9 | 73.2 |
| | Hardwoods | | | | |
| Plot ‡ ($n$ = 454) | DD5 (> 5° C) [b] | 2924.2 | 1106.0 | 1233.0 | 5655.0 |
| | MAT (° C) | 10.3 | 5.3 | 1.5 | 20.5 |
| DWD piece ($n$ = 2,246) | $DIA_{SM}$ (cm) | 10.4 | 5.3 | 7.6 | 76.2 |
| | $DIA_{LG}$ (cm) | 18.4 | 10.0 | 7.6 | 111.8 |
| | LEN (m) | 6.0 | 4.8 | 0.9 | 61.0 |

† Variables: number of degree days (DD5); mean annual temperature (MAT); DWD large- ($DIA_{LG}$) and small-end diameter ($DIA_{SM}$); length (LEN)

‡ Climate data obtained from USFS (2012)

**Table 2**

| Species group | Climate regime † | *n* ‡ | $T_{HALF}$ | $T_{LIBRES}$ | $T_{CONRES}$ | *k* (SE) § |
|---|---|---|---|---|---|---|
| Conifers | MAT < 2.8 | 546 | 22 | 66 | 95 | 0.024 ($9.2x10^{-5}$) |
| | 2.8 ≤ MAT < 4.2 | 648 | 21 | 64 | 93 | 0.024 ($9.1x10^{-5}$) |
| | 4.2 ≤ MAT < 7.3 | 390 | 20 | 58 | 83 | 0.025 ($9.3x10^{-5}$) |
| | 7.3 ≤ MAT < 13.7 | 122 | 17 | 45 | 63 | 0.038 ($1.5x10^{-4}$) |
| | MAT ≥ 13.7 | 415 | 14 | 35 | 48 | 0.040 ($1.1x10^{-4}$) |
| | | | | | | |
| Hardwoods | MAT < 2.8 | 178 | 11 | 59 | 75 | 0.043 ($4.9x10^{-4}$) |
| | 2.8 ≤ MAT < 4.2 | 345 | 11 | 56 | 72 | 0.043 ($3.6x10^{-4}$) |
| | 4.2 ≤ MAT < 7.3 | 493 | 11 | 52 | 66 | 0.045 ($2.2x10^{-4}$) |
| | 7.3 ≤ MAT < 13.7 | 736 | 9 | 36 | 55 | 0.052 ($1.9x10^{-4}$) |
| | MAT ≥ 13.7 | 464 | 8 | 26 | 47 | 0.064 ($2.9x10^{-4}$) |

† Mean annual temperature (MAT; ° C ) obtained from USFS (2012); group cutoffs are the 0.2, 0.4, 0.6, and 0.8 quantiles of the data

‡ Number of downed woody debris piece observations (*n*)

§ $R^2$ ranged from 0.88 to 0.98 (conifers) and from 0.67 to 0.93 (hardwoods)

**Table 3**

| **Species** | ***n*** **†** | $T_{HALF}$ | $T_{LIBRES}$ | $T_{CONRES}$ | ***k*** **(SE) ‡** |
|---|---|---|---|---|---|
| Conifers | | | | | |
| *Abies balsamea* | 527 | 20 | 63 | 87 | 0.023 ($1.0x10^{-4}$) |
| *Juniperus virginiana* | 51 | 17 | 50 | 70 | 0.027 ($2.3x10^{-4}$) |
| *Picea glauca* | 28 | 20 | 63 | 86 | 0.025 ($3.5x10^{-4}$) |
| *Picea mariana* | 281 | 21 | 66 | 90 | 0.025 ($1.1x10^{-4}$) |
| *Picea rubens* | 75 | 20 | 61 | 84 | 0.027 ($1.4x10^{-4}$) |
| *Pinus banksiana* | 301 | 22 | 68 | 94 | 0.025 ($1.2x10^{-4}$) |
| *Pinus echinata* | 46 | 14 | 37 | 50 | 0.039 ($2.9x10^{-4}$) |
| *Pinus elliottii* | 36 | 12 | 30 | 40 | 0.048 ($3.1x10^{-4}$) |
| *Pinus resinosa* | 48 | 20 | 63 | 87 | 0.023 ($3.3x10^{-4}$) |
| *Pinus strobus* | 77 | 19 | 59 | 82 | 0.024 ($2.9x10^{-4}$) |
| *Pinus taeda* | 222 | 13 | 35 | 47 | 0.041 ($1.4x10^{-4}$) |
| *Pinus virginiana* | 132 | 15 | 41 | 57 | 0.037 ($1.7x10^{-4}$) |
| *Thuja occidentalis* | 184 | 20 | 61 | 83 | 0.026 ($1.1x10^{-4}$) |
| All conifers | 2097 | 18 | 57 | 80 | 0.028 ($6.4x10^{-5}$) |
| Hardwoods | | | | | |
| *Acer rubrum* | 167 | 10 | 47 | 71 | 0.048 ($4.2x10^{-4}$) |
| *Acer saccharinum* | 22 | 9 | 43 | 61 | 0.058 ($9.6x10^{-4}$) |
| *Acer saccharum* | 113 | 10 | 50 | 75 | 0.045 ($6.9x10^{-4}$) |
| *Betula alleghaniensis* | 36 | 11 | 56 | 84 | 0.045 ($6.5x10^{-4}$) |
| *Betula papyrifera* | 219 | 11 | 56 | 84 | 0.045 ($3.4x10^{-4}$) |
| *Fagus grandifolia* | 44 | 10 | 48 | 72 | 0.047 ($6.7x10^{-4}$) |
| *Fraxinus nigra* | 30 | 11 | 54 | 81 | 0.045 ($7.4x10^{-4}$) |
| *Liquidambar styraciflua* | 48 | 8 | 32 | 44 | 0.063 ($9.2x10^{-4}$) |
| *Liriodendron tulipifera* | 21 | 9 | 40 | 56 | 0.057 ($1.0x10^{-3}$) |
| *Populus balsamifera* | 39 | 11 | 53 | 80 | 0.046 ($8.4x10^{-4}$) |
| *Populus grandidentata* | 44 | 10 | 51 | 77 | 0.046 ($7.9x10^{-4}$) |
| *Populus tremuloides* | 218 | 11 | 61 | 89 | 0.043 ($4.6x10^{-4}$) |
| *Prunus serotina* | 20 | 10 | 48 | 76 | 0.053 ($1.7x10^{-3}$) |
| *Quercus alba* | 84 | 9 | 38 | 54 | 0.048 ($6.4x10^{-4}$) |
| *Quercus falcata* | 34 | 8 | 33 | 45 | 0.057 ($9.2x10^{-4}$) |
| *Quercus nigra* | 34 | 8 | 29 | 39 | 0.076 ($1.2x10^{-3}$) |
| *Quercus prinus* | 40 | 9 | 44 | 63 | 0.049 ($7.8x10^{-4}$) |
| *Quercus rubra* | 124 | 10 | 49 | 73 | 0.053 ($5.2x10^{-4}$) |
| *Quercus stellata* | 27 | 9 | 36 | 50 | 0.060 ($1.0x10^{-3}$) |
| *Quercus velutina* | 94 | 9 | 40 | 57 | 0.054 ($5.8x10^{-4}$) |
| *Sassafras albidum* | 27 | 9 | 42 | 59 | 0.055 ($9.7x10^{-4}$) |
| *Tilia americana* | 21 | 10 | 47 | 70 | 0.047 ($1.4x10^{-3}$) |
| *Ulmus americana* | 74 | 9 | 44 | 64 | 0.050 ($5.8x10^{-4}$) |
| All hardwoods | 2212 | 10 | 46 | 69 | 0.050 ($1.4x10^{-4}$) |

† Number of observations (*n*)

‡ $R^2$ ranged from 0.86 to 0.99 (conifers) and from 0.68 to 0.94 (hardwoods)

**Figure legends**

**Figure 1** Proportion of original biomass remaining for downed woody debris pieces across eastern US forests using a decay class and volume reduction factor approach. Segments within each figure denote the half-life (A) and liberal (B) and conservative (C) estimates of residence time, where B and C are defined as the number of years when the biomass curve falls to within two and one standard error(s), respectively, of the reduction factor for a decay class 5 piece. Error bars denote ± one standard deviation.

**Figure 2** Estimated downed woody debris half-lives ($T_{HALF}$) and liberal ($T_{LIBRES}$) and conservative ($T_{CONRES}$) estimates of residence time for selected conifer and hardwood species for long- (L), medium- (M), and short- (S) length pieces. Length class cutoffs were taken as the 0.33 and 0.67 quantiles of the data within a species.

**Figure 3** Comparisons of downed woody debris half-lives ($T_{HALF}$; a) and decay rate parameters ($k$; b) determined in this study with published estimates for individual species in eastern US forests. For detailed discussion of individual species, see text.

**Figure 4** Projected downed woody debris (DWD) C flux for current (2007-2011) DWD C stocks in various forest type groups across the eastern US.

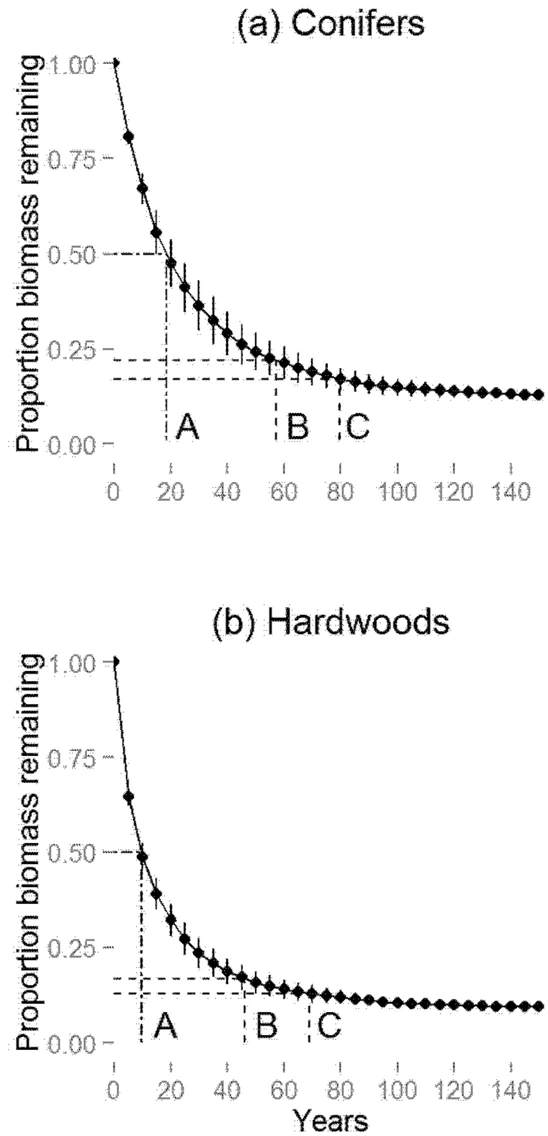


Figure 1 Proportion of original biomass remaining for downed woody debris pieces across eastern US forests using a decay class and volume reduction factor approach. Segments within each figure denote the half-life (A) and liberal (B) and conservative (C) estimates of residence time, where B and C are defined as the number of years when the biomass curve falls to within two and one standard error(s), respectively, of the reduction factor for a decay class 5 piece. Error bars denote ± one standard deviation.

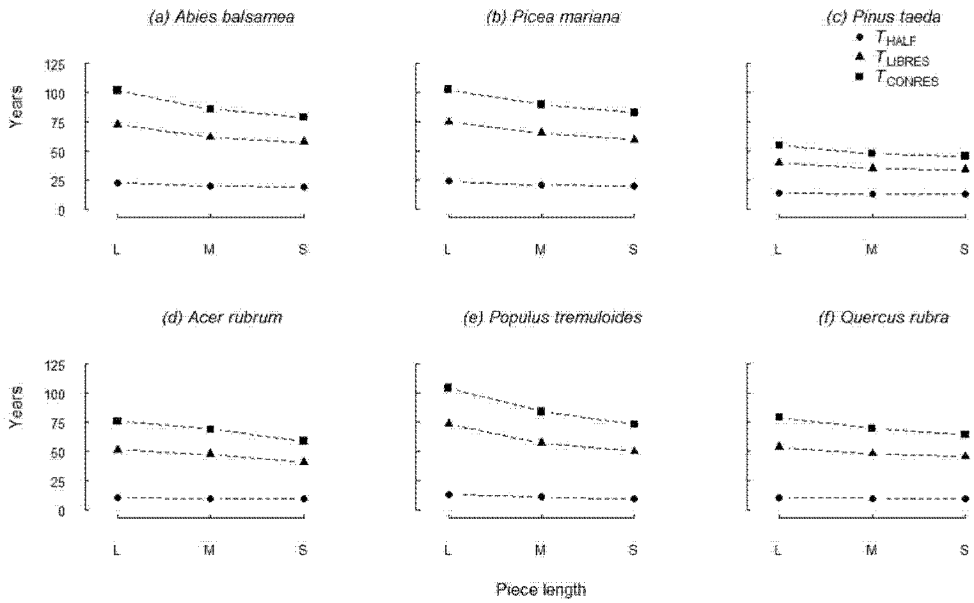


Figure 2 Estimated downed woody debris half-lives (THALF) and liberal (TLIBRES) and conservative (TCONRES) estimates of residence time for selected conifer and hardwood species for long- (L), medium- (M), and short- (S) length pieces. Length class cutoffs were taken as the 0.33 and 0.67 quantiles of the data within a species.

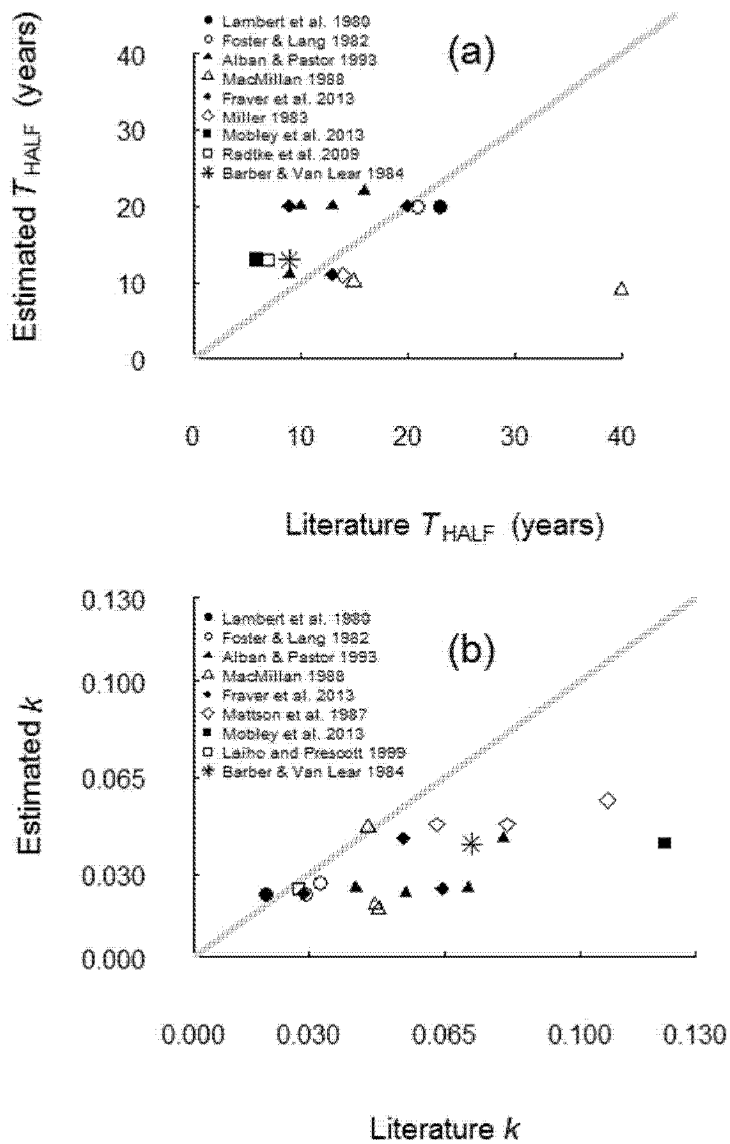


Figure 3 Comparisons of downed woody debris half-lives (THALF; a) and decay rate parameters (k; b) determined in this study with published estimates for individual species in eastern US forests. For detailed discussion of individual species, see text.

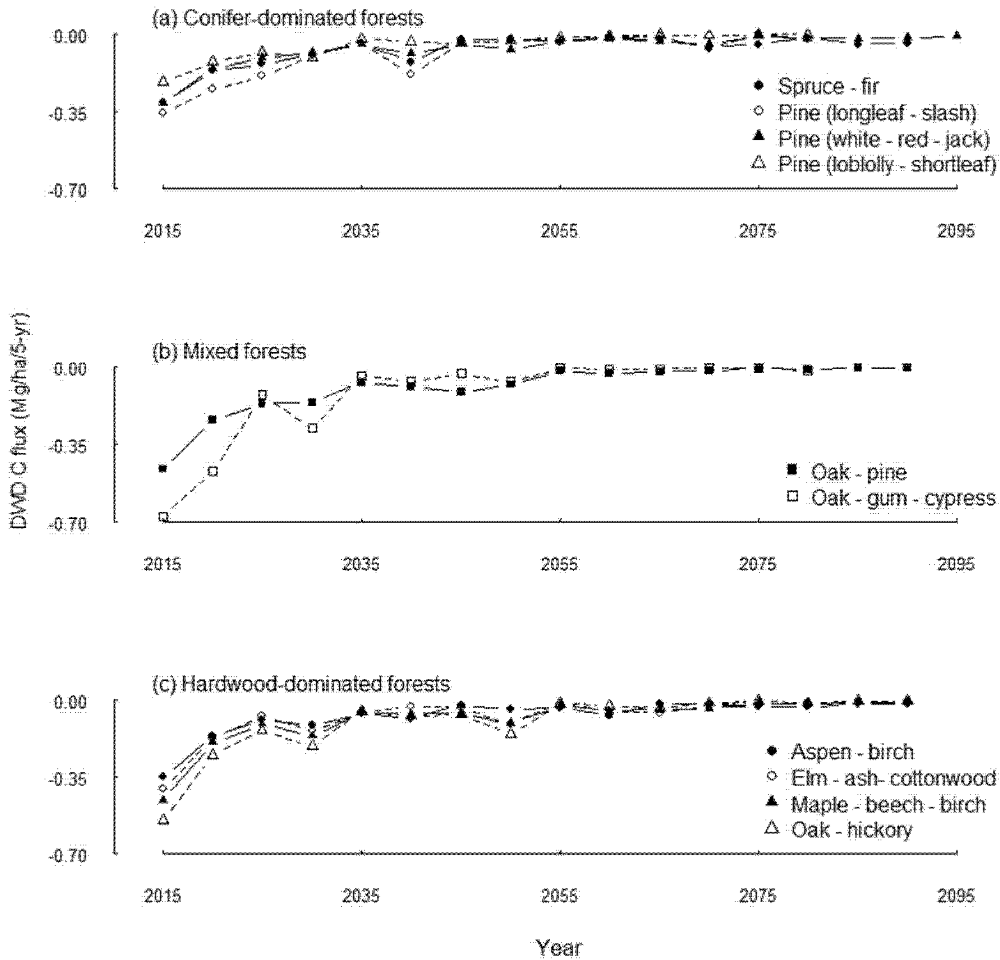


Figure 4 Projected downed woody debris (DWD) C flux for current (2007-2011) DWD C stocks in various forest type groups across the eastern US.

| | |
|---|---|
| **From:** | Miner, Reid |
| **To:** | Ohrel, Sara |
| **CC:** | John Barnwell |
| **Sent:** | 1/30/2014 10:02:22 AM |
| **Subject:** | Carbon accounting paper |
| **Attachments:** | DRAFT 22 Jan 2014 Forest Carbon Accounting Considerations in U.S. Bioenergy Policy.docx |

Hello Sara
Thank you for taking the time to chat with us yesterday.
We wanted to be sure you had the most recent version of the carbon accounting paper.
I think you will find that the attached version, which has been submitted to the Journal of Forestry, is essentially the same as the older version you have but has been tightened up (reflecting comments we received on earlier versions). As this draft is still being reviewed by the Journal of Forestry, we would ask that you not distribute it beyond the few individuals in EPA who might benefit from seeing it. With a bit of luck we will have a final published paper to share with you soon.
If you have questions, please let me know.
Best Regards
Reid

*Reid Miner, Vice President-Sustainable Manufacturing*
*NCASI*
*P.O.Box 13318*
*Research Triangle Park, NC 27709*
*Phone +1 (919) 600-1022*
*Email: RMiner@ncasi.org*

---

| | |
|---|---|
| **From:** | Montanez, Jessica |
| **To:** | Ohrel, Sara |
| **CC:** | Kornylak, Vera S. |
| **Sent:** | 1/28/2014 8:54:30 AM |
| **Subject:** | RE: questions/ideas for tomorrow |
| **Attachments:** | BiomassSABFinalReport.pdf |

I am not sure. I saw that suggestion from the comments we received as part of the SAB review of the framework. See the SAB report executive summary page 10.

Jessica

Jessica Montañez
Office of Air Quality Planning and Standards
Air Quality Policy Division
New Source Review Group
109 TW Alexander Drive MD: C504-03 RTP, NC 27711
Phone: 919-541-3407, Fax: 919-541-5509
Note: Positions or views expressed here do not represent official EPA policy.

Looking for a speaker for your school or community event? http://www.epa.gov/rtpspeakers/

---

**From:** Ohrel, Sara
**Sent:** Tuesday, January 28, 2014 8:41 AM
**To:** Montanez, Jessica
**Cc:** Kornylak, Vera S.
**Subject:** RE: questions/ideas for tomorrow

Hello again,
This looks fine. One question – Ex. 5 - Deliberative
Ex. 5 - Deliberative
Thanks!

Sara

---

**From:** Montanez, Jessica
**Sent:** Tuesday, January 28, 2014 8:33 AM
**To:** Ohrel, Sara
**Cc:** Kornylak, Vera S.
**Subject:** RE: questions/ideas for tomorrow

Hi Sara,

Does the plan below sound good? I am working from home today due to the possible snow event here in RTP, but I am accessible by phone Ex. 6 - Personal Privacy and email.

Jessica

Jessica Montañez
Office of Air Quality Planning and Standards
Air Quality Policy Division
New Source Review Group
109 TW Alexander Drive MD: C504-03 RTP, NC 27711
Phone: 919-541-3407, Fax: 919-541-5509
Note: Positions or views expressed here do not represent official EPA policy.

Looking for a speaker for your school or community event? http://www.epa.gov/rtpspeakers/

---

**From:** Montanez, Jessica
**Sent:** Monday, January 27, 2014 5:06 PM
**To:** Ohrel, Sara
**Cc:** Kornylak, Vera S.
**Subject:** RE: questions/ideas for tomorrow

Hi Sara,

Thanks. So are we still good with the following plan?

1.
2.

**Ex. 5 - Deliberative**

3. Q and A's

Some of the Q and A's that we have been thinking about are?

1.
2.

**Ex. 5 - Deliberative**

3.
4.
5.

Jessica Montañez
Office of Air Quality Planning and Standards
Air Quality Policy Division
New Source Review Group
109 TW Alexander Drive MD: C504-03 RTP, NC 27711
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Note: Positions or views expressed here do not represent official EPA policy.

Looking for a speaker for your school or community event? http://www.epa.gov/rtpspeakers/

---

**From:** Ohrel, Sara
**Sent:** Monday, January 27, 2014 3:55 PM
**To:** Montanez, Jessica; Kornylak, Vera S.
**Subject:** questions/ideas for tomorrow

Hi Jessica and Vera,
I will be putting together slides for tomorrow this evening – if you can forward to the list of questions/ideas that you

have been brainstorming today, I will do my best to incorporate them.
Thanks!

Sara Bushey Ohrel
Climate Economics Branch
Climate Change Division
U.S. Environmental Protection Agency
Phone: (202) 343-9712
Cell: (202) 341-6748

--this email is deliberative--do not distribute or cite--

| | |
|---|---|
| **From:** | Ohrel, Sara |
| **To:** | Baker, Justin |
| **CC:** | Cole, Jefferson |
| **Sent:** | 1/23/2014 1:54:14 PM |
| **Subject:** | RE: Draft Appendices and Main Document |
| **Attachments:** | AF2 main body 1 11 14.docx |

This is the most recent draft. **Ex. 5 - Deliberative**
Please do not distribute or cite.
Thanks!

---

**From:** Baker, Justin [mailto:justinbaker@rti.org]
**Sent:** Thursday, January 23, 2014 10:36 AM
**To:** Ohrel, Sara
**Cc:** Cole, Jefferson
**Subject:** RE: Draft Appendices and Main Document

Also, are there more recent versions that I should forward?

I'm not sure how current my version of the main document is.

Justin

---

**From:** Ohrel, Sara [mailto:Ohrel.Sara@epa.gov]
**Sent:** Thursday, January 23, 2014 10:18 AM
**To:** Baker, Justin
**Cc:** Cole, Jefferson
**Subject:** RE: Draft Appendices and Main Document

I do it all the time too - sorry Jeff J
Perfect, thanks JB.

---

**From:** Baker, Justin [mailto:justinbaker@rti.org]
**Sent:** Thursday, January 23, 2014 10:17 AM
**To:** Ohrel, Sara
**Cc:** Cole, Jefferson
**Subject:** RE: Draft Appendices and Main Document

Sorry, Jeff. Sometimes I'm quick on the email trigger!

Duly noted on the Main Doc.

Also, I owe you text explaining **Ex. 5 - Deliberative** I'll try to have that to you by noon.

---

**From:** Ohrel, Sara [mailto:Ohrel.Sara@epa.gov]
**Sent:** Thursday, January 23, 2014 10:13 AM
**To:** Baker, Justin
**Cc:** Cole, Jefferson
**Subject:** RE: Draft Appendices and Main Document

Adding Jeff's work email J

---

**From:** Ohrel, Sara
**Sent:** Thursday, January 23, 2014 10:12 AM

**To:** 'Baker, Justin'; Jefferson Cole
**Subject:** RE: Draft Appendices and Main Document

Sure. One huge caveat: THINGS MAY and ARE LIKELY to CHANGE in the main document, section 4.

---

**From:** Baker, Justin [mailto:justinbaker@rti.org]
**Sent:** Thursday, January 23, 2014 10:10 AM
**To:** Ohrel, Sara; Jefferson Cole
**Subject:** Draft Appendices and Main Document

Dear Sara and Jeff,

Katie Hanks and Stephen Boone at RTI asked whether they could start looking over draft documents just to get up to speed on this work and to start thinking about the regulatory side. Obviously, all drafts will be kept within a tight circle at RTI.

Is it ok to start sharing these drafts?

Thanks,
Justin

**From:** Ohrel, Sara
**To:** Latta, Greg
**CC:** Cole, Jefferson; Baker, Justin
**Sent:** 1/23/2014 12:13:58 PM
**Subject:** FW: Dimensionless SITE TNC in Reference Point --deliberative--
**Attachments:** App E_RP Baseline_01-03_clean_w comment-resp so 1 9_19.docx; Appendix G_Case Studies_01-15-2014 clean.docx; State of Reference Point Baseline Equation - Current and Future - JCole.docx; TO 003_REVISED_Appendix G_Spreadsheet_01-21-2014 - JC Edits.xlsx

Hi Greg,
We would like to ask if you could work a bit on the reference point side of things today:

1)

2) **Ex. 5 - Deliberative**

Thanks!

---

**From:** Cole, Jefferson
**Sent:** Wednesday, January 22, 2014 3:29 PM
**To:** Ohrel, Sara; greg.latta@oregonstate.edu; Baker, Justin; Beach, Robert H.
**Subject:** Dimensionless SITE TNC in Reference Point --deliberative--

*Or, how one can be stateless yet full of meaning...*

Team,

As I mentioned, attached is both my thought-piece/walkthrough for how **Ex. 5 - Deliberative**
**Ex. 5 - Deliberative**

Better to read the word file first before digging into the spreadsheet. I'm pretty sure I got all my math correct here, but a double-check would always be appreciated.

For the spreadsheet, **Ex. 5 - Deliberative**
**Ex. 5 - Deliberative**

For all the sensitivity cases, I tried to highlight in yellow the terms in my calculations that are being manipulated to avoid confusion (hopefully).

Anyhow, let me know if you have any questions. Importantly, after you've digested this, I'd be curious to hear proposals on
**Ex. 5 - Deliberative**

Best,

Jeff

Jefferson Cole
Climate Economics Branch
Climate Change Division
U.S. Environmental Protection Agency
cole.jefferson@epa.gov
202.343.9671

---

| | |
|---|---|
| **From:** | Ohrel, Sara |
| **To:** | Flugge, Mark |
| **CC:** | Cole, Jefferson |
| **Sent:** | 1/20/2014 12:40:43 PM |
| **Subject:** | RE: (EP-BPA-12-H-0022, EP-B12H-00125/TO 003, Task 6) Joint appendix text and tables (and supporting spreadsheet) |
| **Attachments:** | TO 003_REVISED_Appendix G_Spreadsheet_01-03-2014so.xlsx |

Hi Mark,

**Ex. 5 - Deliberative**

Thanks!

---

**From:** Ohrel, Sara
**Sent:** Monday, January 20, 2014 11:45 AM
**To:** 'Flugge, Mark'
**Cc:** Cole, Jefferson
**Subject:** FW: (EP-BPA-12-H-0022, EP-B12H-00125/TO 003, Task 6) Joint appendix text and tables (and supporting spreadsheet)

Hello Mark,
Can you please either confirm the exact units used for each case study calculation (as reflected in the column headers) or update each as needed in the attached excel as soon as possible?
Thank you,
Sara

---

**From:** Flugge, Mark [mailto:Mark.Flugge@icfi.com]
**Sent:** Tuesday, January 07, 2014 11:54 AM
**To:** Jenkins, Jennifer
**Cc:** Ohrel, Sara; Sherry, Christopher; Cole, Jefferson; Steele, Rachel
**Subject:** (EP-BPA-12-H-0022, EP-B12H-00125/TO 003, Task 6) Joint appendix text and tables (and supporting spreadsheet)

Hi Jen: please find attached the joint appendix text and tables (and supporting spreadsheet) for the reference point baseline for TO 003: *Revisions to Accounting Framework for GHG Emissions from Bioenergy and Other Biogenic Sources*.

Best regards,
Mark and Rachel

**MARK FLUGGE** | Manager | 202.862.1231 (o) | Mark.Flugge@icfi.com | icfi.com
**ICF INTERNATIONAL** | 1725 I Street NW, Suite 1000, Washington, DC 20006 | 202.862.1144 (f)
Connect with us on social media.

---

**From:** Ohrel, Sara [mailto:Ohrel.Sara@epa.gov]
**Sent:** Monday, December 30, 2013 12:54 PM
**To:** Ohrel, Sara; Flugge, Mark; Baker, Justin; Latta, Greg; Beach, Robert H.
**Cc:** Jenkins, Jennifer; Cole, Jefferson; Sherry, Christopher
**Subject:** RE: direction for joint baseline appendix

Attached you will find the draft outline for the joint appendix as well as the related spreadsheet that has templates for all the sensitivities that correspond with the directions below.

Sara Bushey Ohrel
Climate Economics Branch
Climate Change Division
U.S. Environmental Protection Agency
Phone: (202) 343-9712
Cell: (202) 341-6748

--this email is deliberative--do not share or cite--

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**From:** Ohrel, Sara
**Sent:** Monday, December 30, 2013 12:35 PM
**To:** Flugge, Mark; 'Baker, Justin'; 'Latta, Greg'; 'Beach, Robert H.'
**Cc:** Jenkins, Jennifer; Cole, Jefferson; Sherry, Christopher
**Subject:** direction for joint baseline appendix

**Direction for Joint Baseline Appendix: 12/30/13**

This technical direction outlines work on the AF2 Joint Baseline Appendix. The work is divided between the respective biomass teams at ICF and RTI, also with support from an USFS-OSU IAA.

**All draft products are due by close of business Tuesday January 7th, unless this deadline otherwise changed by EPA.**

Ex. 5 - Deliberative

# Ex. 5 - Deliberative

As soon as EPA receives and reviews the above components, we will then work with you all to task out the next round of responsibilities on this appendix. These tasks will likely include reviewing sections completed by others and working to fill in the subsections that discuss similarities/differences in results/key takeaways between the baseline approaches. Jen, please add anything that I have missed.

**Please let us know if you have any questions or need further clarification on any of the above. Please confirm receipt and deliverable date.**

We are in the final stretch of the AF2 and appreciate your support.

Thank you!
Sara

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--this email is deliberative--do not share or cite--

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